QUANTITATIVE ANALYSES OF UNIT TRAIN SAFETY AND RAILROAD TANK CAR IMPLEMENTATION POLICY

BY

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THESIS

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ABSTRACT

Railroads play a critical role in the transportation and economic prosperity of North America. Train safety has improved considerably over the past decade. However, with the large volume of traffic, accidents still occur. Derailments are the most common type of train accident recorded in the Federal Railroad Administration's Rail Equipment Accident/Incident database. The research presented in this thesis focuses on derailments and releases of hazardous materials, specifically three topics related to this general theme: unit train loading condition, the effect of train configuration on risk, and policies for implementation schedule for safer tank cars.

The effect of loading condition on unit-train derailment occurrence, causes and severity is described in Chapter 2. An algorithm was developed to identify derailments of loaded and empty unit trains on mainlines and sidings recorded in the Federal Railroad Administration database. A dataset of these accidents for the 15-year period from 2001 to 2015 was developed and analyzed. The frequency of derailments for both loaded and empty unit trains declined by more than 50%. The average number of cars derailed per accident fluctuated for both loading conditions but showed no particular trend. Approximately five times more loaded unit train derailments were recorded than empty unit trains but in the absence of specific unit train traffic data, inferences about rates are not possible. Loaded unit trains were more than four times heavier than empty unit trains, and loaded train derailments tended to involve more cars than empty train derailments. The distribution of derailment causes differed for loaded and empty unit trains. Loaded trains most frequently derailed due to broken rails and welds, while the leading cause of empty train derailments was obstructions, which included severe weather. Over 90% of the

derailments of loaded and empty unit trains considered in this study occurred on mainline tracks, and the distribution of causes differed between mainline and siding tracks.

Chapter 3 presents an analysis of the risk associated with transporting hazardous materials by unit trains versus manifest trains. While unit trains offer efficient transportation of hazardous materials, if these trains derail, the consequences can be particularly severe. Transporting hazardous materials in unit trains reduces exposure to accidents compared to transporting the same quantity of material in a larger number of manifest trains. However, in the event that a derailment of a unit train does occur, the consequences may be greater. Conversely, transportation in a larger number of manifest trains increases the exposure to derailments, but may reduce the severity if an accident occurs. An investigation of these trade-offs using the Multiple Tank Car Release model to conduct a series of simulations is presented. As part of this analysis the effect of using DOT 111 tank cars was compared to use of DOT 117 tank cars. Both the likelihood and consequence of transporting hazardous materials in these different train configurations were estimated and the metrics used to estimate risk were the distributions of number of tank cars derailed, number of tank cars releasing, and quantity released.

Use of safer tank car specifications can substantially reduce the consequences and risk of derailments involving hazardous materials. Nevertheless, there are practical and financial considerations associated with replacing the existing fleet with new cars. Safer tank cars are generally more expensive to build and operate, and there may be practical constraints due to manufacturing capacity. In the late 2000s, the government and industry were faced with a choice of immediate adoption of a safer tank car for Toxic Inhalation Hazard materials, or awaiting the results of a research and development project to develop an even safer car. The discussion between the government and industry regarding phase-in policies for safer tank cars led to the research described in Chapter 4. Specifically, how would different policies regarding deferral of the decision to implement safer cars, and the schedule of replacement affect risk. In Chapter 4, a methodology is presented to quantify the risk associated with rail transport of the top two toxic inhalation hazard materials by shipment, ammonia and chlorine. A network risk analysis model was used in conjunction with routing information, population, and the Multiple Tank Car Release model to estimate several risk metrics under different implementation scenarios.

To My Mom

ACKNOWLEDGEMENTS

First, I would like to start by thanking my mentors. I am grateful to have a wonderful advisor, Professor Christopher P.L. Barkan whose encouragement and constructive advice has helped me tremendously. It has been a rewarding journey to work for someone who is resourceful, always curious and has high standard for the quality of work. Special thanks to Rapik Saat, who was my advisor when I was an undergraduate student, for providing me with an opportunity to work at the Rail Transportation and Engineering Center (RailTEC) and for his help and guidance when I first started research. Special thanks to Manuel Martin Ramos for his mentorship that led to my research today.

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TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

Railroads play a critical role in the transportation and economic prosperity of North America. Train safety has improved considerably over the past decade and this trend continues; in 2016 the derailment rate was the lowest it has been since the Federal Railroad Administration (FRA) began recording data. Nevertheless, with the large volume of traffic, accidents still occur. Derailments are the most common type of train accidents recorded in the FRA's Rail Equipment Accident/Incident (REA) database, comprising almost 70% of these accidents in the fifteen-year period from 2001 to 2015. Freight train derailments, especially those involving hazardous materials, have the potential to cause casualties and serious damage if there is a release of these materials. Such accidents have received increased attention from the railroad industry and the government in recent years due to the expanded transportation of flammable liquids and several high-profile derailments involving these products, along with ongoing concern regarding improving the safety of rail transport of toxic inhalation hazard (TIH) materials. The research presented in this thesis focuses on derailments and releases of hazardous materials, specifically three topics related to this general theme: unit train loading condition, the effect of train configuration on risk, and policies for implementation schedule for safer tank cars.

The use of unit trains has expanded substantially over the past century due to improvements in economies of scale and operating efficiency that they offer. Recent growth in North American production of flammable liquids has led to substantially expanded use of unit-train transportation for these products over the past decade and a half (NASEM, 2017). Because of this, there is increased interest in factors affecting the safety of unit trains. Limited previous research has focused on the effect of loading conditions on derailment characteristics. In Chapter 2, I present a quantitative analysis of the derailment characteristics of loaded and empty unit trains, with specific attention to the relationship between unit train loading condition, and derailment occurrence and causes. I describe a methodology to identify loaded and empty unit trains in the FRA database and then present an analysis of the frequency and the severity of mainline derailments based on train loading condition. I also present an analysis of the most frequent causes of derailments for these two loading conditions of unit trains.

While unit trains offer efficient transportation of hazardous materials, if these trains derail, the consequences can be particularly severe. Transporting hazardous materials in unit trains reduces exposure to accidents compared to transporting the same quantity of material in a larger number of manifest trains. However, in the event that a derailment of a unit train does occur, the consequences may be greater. Conversely, transportation in a larger number of manifest trains increases the exposure to derailments, but may reduce the severity if an accident occurs. In Chapter 3, I investigate these trade-offs using the Multiple Tank Car Release (MTCR) model to conduct a series of simulations. As part of this analysis I also consider the effect of using safer tank cars in these different train configurations. I estimated both the likelihood and consequence of transporting hazardous materials. The metrics used to estimate risk are the distributions of number of tank cars derailed, number of tank cars releasing, and quantity released.

Use of safer tank car specifications can substantially reduce the consequences and risk of derailments involving hazardous materials. Nevertheless, there are practical and financial considerations associated with replacing the existing fleet with new cars. Safer tank cars are generally more expensive to build and operate, and there may be practical constraints due to manufacturing capacity. In the late 2000s, the government and industry were faced with a choice of immediate adoption of a safer tank car for Toxic Inhalation Hazard (TIH) materials, or awaiting the results of a research and development project to develop an even safer car. The discussion between the government and industry regarding phase-in policies for safer tank cars led to the research described in Chapter 4. Specifically, how would different policies regarding deferral of the decision to implement safer cars, and schedule of replacement affect risk. In Chapter 4, I present a methodology to quantify the risk associated with rail transport of the top two TIH materials by shipment, ammonia and chlorine. I used a network risk analysis model in conjunction with routing information, population, and the MTCR model to estimate several risk metrics under differing implementation scenarios.

Chapters 2, 3, and 4 are each written as stand-alone papers. The paper that Chapter 2 is adapted from has been accepted for publication in the Transportation Research Record. Chapters 3 and 4 will be further refined and submitted for consideration for future publication in peer-reviewed journals. In Chapter 5, I summarize the insights and lessons learned from this research that can be incorporated into development and evaluation of risk mitigation strategies and policies, and also present some suggestions for future research.

REFERENCE

National Academies of Sciences, Engineering, and Medicine (NASEM), Transportation Research Board (TRB); Policy Studies; Studies and Special Programs Division; Committee for a Study of Domestic Transportation of Petroleum, Natural Gas, and Ethanol. 2017. *Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape*. Transportation Research Board Special Report 325. Transportation Research Board, Washington, D.C.

CHAPTER 2: QUANTITATIVE ANALYSIS OF THE DERAILMENT CHARACTERISTICS OF LOADED AND EMPTY UNIT TRAINS

Adapted from
Li, W., G. Roscoe, Z. Zhang, M.R. Saat and C.P.L. Barkan.
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Introduction

Railroads play a critical role in the transportation and economic prosperity of the North America. Train safety has improved considerably over the past decade. This trend continues; in 2016 the derailment rate was the lowest it has been since the Federal Railroad Administration (FRA) began recording data. Nevertheless, with the large volume of traffic, accidents still occur. Derailments are the most common type of train accident recorded in the FRA's Rail Equipment Accident/Incident (REA) database, comprising almost 70% of these accidents in the fifteen-year period from 2001 to 2015. Freight train derailments, especially those involving hazardous materials, have the potential to cause serious damage if there is a release of these materials. These types of accidents have received increased attention from the rail industry and the government in recent years due to the expansion in transportation of flammable liquids and several high-profile derailments involving these products.

Unit trains are a specific type of rail service in which an entire train transports a single commodity from one origin to one destination. Unit trains increase the efficiency of railroad freight transportation by reducing operating expenses, using bulk loading, improving asset utilization, reducing transit time, and in general creating economies of scale (Grimes, 1981;

Grimes, 1982; Starr, 1976). Historically, unit trains transported coal and certain other bulk commodities (Starr, 1976). More recently, flammable liquid tank cars have begun traveling in unit train like movements (NASEM, 2017). For the purposes of this paper, “unit trains” will refer to fully loaded or empty trains having train type prefixes designating them as unit trains. These were determined from the “train number” column in the REA database; however, a more precise definition of unit trains can be found in Starr (1976). In terms of loading condition, unit trains are either fully loaded or empty. Most previous research on unit trains has focused on operational and economic questions, such as their productivity and profitability (Cacchiani et al., 2012; Clow, 1998; Grimes, 1981; Grimes, 1982; Starr, 1976).

Previous research on train operating safety has included analyses of derailment frequency and consequences based on train speed (Yang et al., 1973) and derailment causes (Barkan et al., 2003; Liu et al., 2012; Schafer and Barkan, 2008), but relatively little attention has been given to the effect of loading condition. Liu et al. (2013a) developed a zero-truncated negative binomial regression model for derailment severity that factors in loading condition; however, the authors are unaware of any prior research specifically focused on the relationship between unit train loading condition and derailment occurrence and cause. In this paper, the frequency and the severity of freight train derailments were analyzed based on different train loading conditions, and the most common derailment causes for each unit train loading condition were investigated.

Research Objective

The objective was to identify and quantify the effect of loading condition on freight train derailments, and to compare their causes for loaded and empty unit trains. To achieve this the following steps were taken:

- Develop a methodology to identify loaded and empty unit trains recorded in the REA database
- Build a database for derailments of loaded and empty unit trains
- Analyze the resulting dataset to quantify the relationship between train loading condition and derailment frequency and severity
- Evaluate the top derailment causes in terms of their frequency and average severity

Methodology

Previous studies have used monetary damage and number of cars derailed (Barkan et al., 2003) to assess the severity of train derailments. In this paper, derailment severity is defined as the average number of cars derailed in an accident; and the frequency of derailments is defined as the number due to a particular cause.

Data Source

The FRA compiles train accident data based on reports submitted by railroads operating in the United States. The train derailment data used in this study were from the REA database. The REA database provides detailed accident information, including operational factors, environmental factors, train characteristics, damage conditions, and other information useful for understanding the circumstances and causes of accidents. Railroads are required to submit reports to the REA database for all accidents that exceed a monetary threshold for damage and loss to infrastructure and equipment (FRA, 2011). This reporting threshold is periodically adjusted to account for inflation, rising from $6,600 in 2001 to $10,500 in 2014 (FRA, 2012). Derailment accidents for Class I railroads over the period from 2001 to 2015 were used for the analysis in this paper.

Classification Method

The REA data were used to develop a dataset that included all Class I railroad derailments of freight trains operating on Class I owned mainline or siding tracks. A total of 6,047 such derailments were recorded for the fifteen-year period studied. To avoid including local trains, derailments of trains with less than 30 cars were excluded, leaving 5,395 for the analysis. Approximately 75% of unit trains subsequently identified in the dataset were greater than 50 cars in length.

An algorithm was developed to identify loaded and empty unit trains in the REA dataset (Figure 2.1). The number of empty cars, the number of loaded cars, and the number of locomotives are recorded in the REA database. Using these fields, the length of a train in terms of total number of cars and locomotives could be calculated. The majority of unit trains transport various non-regulated commodities; however, those transporting hazardous materials generally have “buffer” cars, as required by federal regulation. Buffer cars are placed between occupied locomotives and cars transporting hazardous materials (FRA, 2005). Buffer cars can be either empty, or loaded with an inert material. To account for the possible presence of buffer cars, a train was classified as loaded if 95% or more of its cars were loaded, or empty if 95% or more of its cars were empty. These percentages were calculated by dividing the number of loaded or empty cars by the total number of cars in the train. Since the buffer car loading condition is independent of the loading condition of the rest of the train, the 95% criterion was used for both loaded and empty unit trains rather than a 100% criterion.

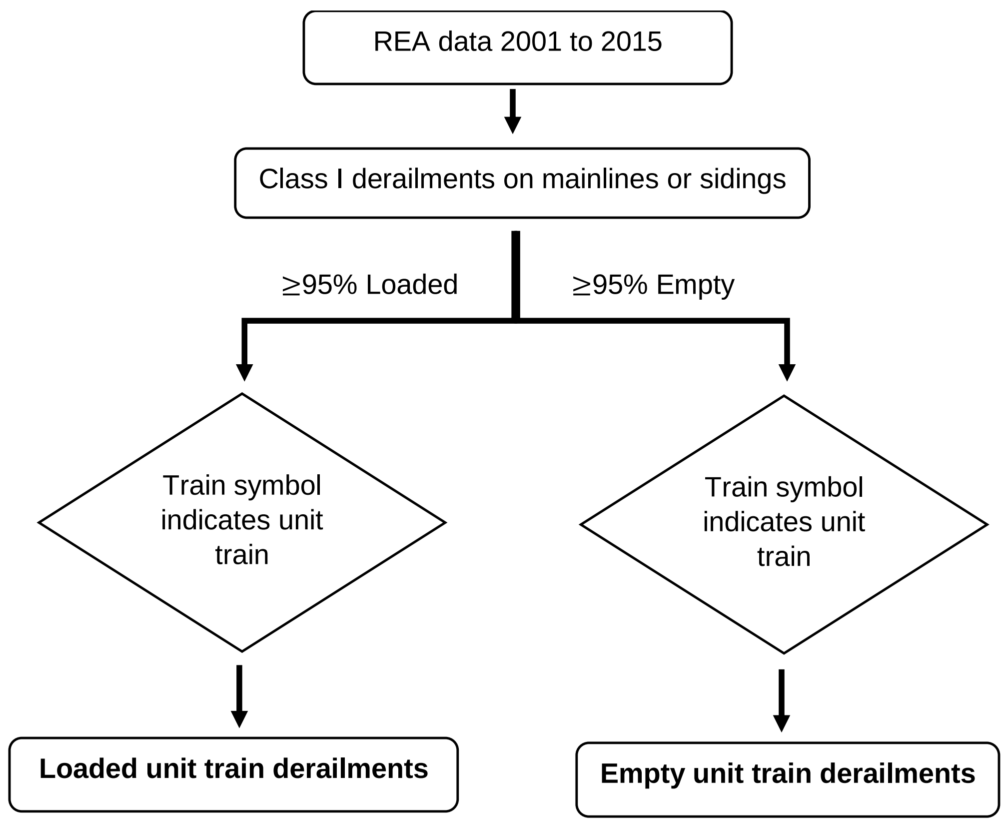


Figure 2.1: Flowchart for Classifying Loaded and Empty Unit Trains

After obtaining all loaded and empty unit train derailments, the remaining derailments were filtered based on their train type. Train type information was obtained using online resources to interpret and classify the "train number" field in the REA database (*RailroadfanWiki*, 2017; *Train Symbol*, 2017). This was done to eliminate derailments that were not bulk unit trains, such as: manifest trains, intermodal trains, local trains, and work trains. Of the remainder, 1,536 derailments were classified as loaded unit trains, 303 were classified as empty unit trains, and 4,180 were classified as "other" trains (Figure 2.1).

Loading-Condition Specific Derailment Analysis

There were about five times more records of loaded trains than empty trains in the dataset. Several pertinent characteristics of these derailments were summarized (Table 2.1), including the tonnage of the train, train length, speed at derailment, number of cars derailed, position-of-derailment (POD), and normalized position-of-derailment (NPOD), where NPOD is the POD normalized by train length (Anderson and Barkan, 2005). Student's t-tests were used to assess the statistical significance of the differences in these characteristics for loaded and empty unit trains. The characteristics of other derailments were also included for comparison.

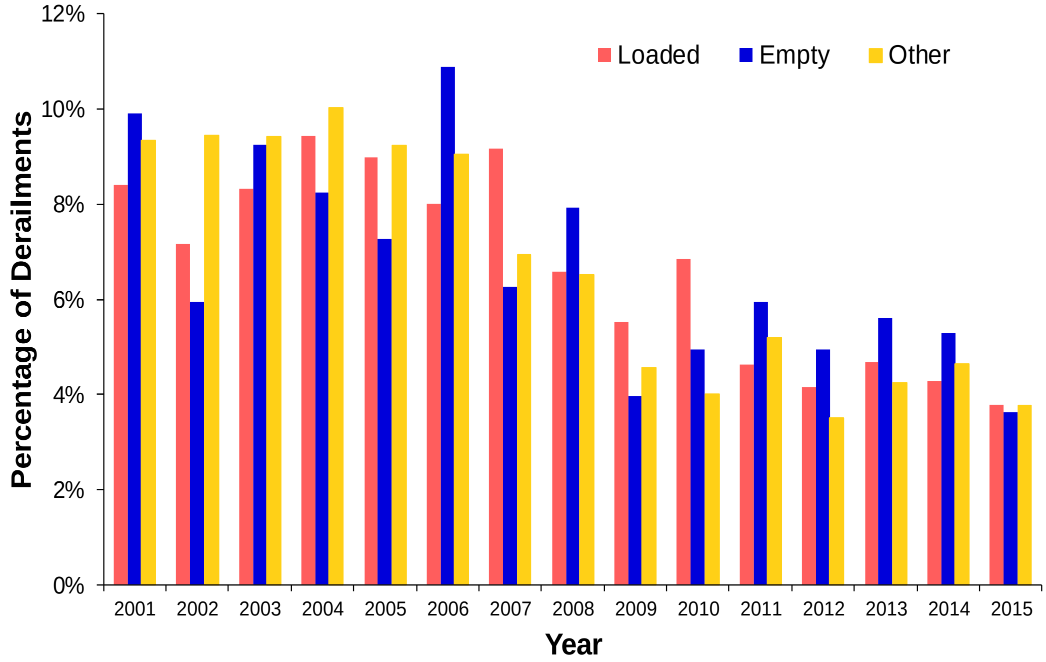
Table 2.1: Summary Statistics of Derailments by Loading Condition

Loading Condition	Number of Accidents	Tons (1,000s)	Average Train Length	Average Speed	Average Number of Cars Derailed	Average POD	Average NPOD
Other	4,180	7.1	77.9	22.5	8.3	11.4	45.0%
Loaded	1,536	14.2	106.9	25.1	11.5	54.4	51.0%
Empty	303	3.0	106.8	24.8	8.9	41.8	40.2%
P-Value	--	<0.001	0.945	0.786	0.001	<0.001	<0.001

Not surprisingly, the weight of loaded unit trains was considerably heavier than empty trains, differing more than four-fold. The average derailment speed of loaded and empty unit trains did not significantly differ (25.1 and 24.8 mph respectively), nor did average train length (106.9 and 106.8 respectively). Empty unit trains derailed an average of 8.9 cars per derailment, while loaded train derailments averaged 11.5 cars or about 30% more, which was also significant. Considering that derailment speed and train length did not differ significantly, but total train weight did, the higher average number of cars derailed is consistent with Liu et al.'s (2013a) results regarding the effect of loading factor. They found that derailment severity depends on derailment speed, residual length, and loading factor. In addition to derailing more cars, the POD and NPOD for loaded unit trains was significantly farther back in the train compared to empty unit trains. This outcome could be due to a difference in derailment cause distributions for loaded and empty trains (Barkan et al., 2003; Liu, 2015).

Derailment Frequency and Severity Trend

The trend in the frequency and severity of derailments was investigated (Figure 2.2). The number of derailments in each of the three categories of train type differed substantially so the data were normalized, and the percentages were used to facilitate comparison. The derailment frequency for loaded unit trains, empty unit trains, and other trains declined by about 55%, 63%, and 60% respectively over the 15-year period (Figure 2.2a). This is consistent with the trend for all derailments, which declined 58% over the 15-year study period. The derailment severity of empty unit trains was generally less than that of loaded unit trains (Table 2.1) but fluctuated widely from year to year (Figure 2.2b). For example, in 2015, derailment severity for empty unit trains was higher than that of loaded unit trains; however, this was due to a single incident in Iowa in which a tornado derailed 87 cars in an empty unit train. Since the sample size for empty unit trains was relatively small, extreme incidents such as this one sometimes shifted the average for a given year. While derailment severity for other trains is less than that of unit trains, it exhibited the same fluctuating trend.



(a)

(b)

Figure 2.2: Derailment (a) Frequency and (b) Severity by Year, 2001 – 2015

Although extreme accidents can influence average derailment severity, they are uncommon. To understand the distribution of derailment frequency and severity, the number of derailments was plotted against the number of cars derailed per accident (Figure 2.3). The cumulative percentage of cars derailed was also used to compare the distributions of the three train loading conditions. The cumulative curve for loaded unit trains was well to the right of the curve for empty unit trains, consistent with the finding that empty unit trains derail fewer cars than loaded. Interestingly, the cumulative curve for "other" trains was similar to the curve for empty unit train derailments. These other trains averaged about 2.4 times heavier than empty unit trains, but they still weighed only half as much on average compared to loaded unit trains. Other trains also averaged about 27% shorter than unit trains (Table 2.1).

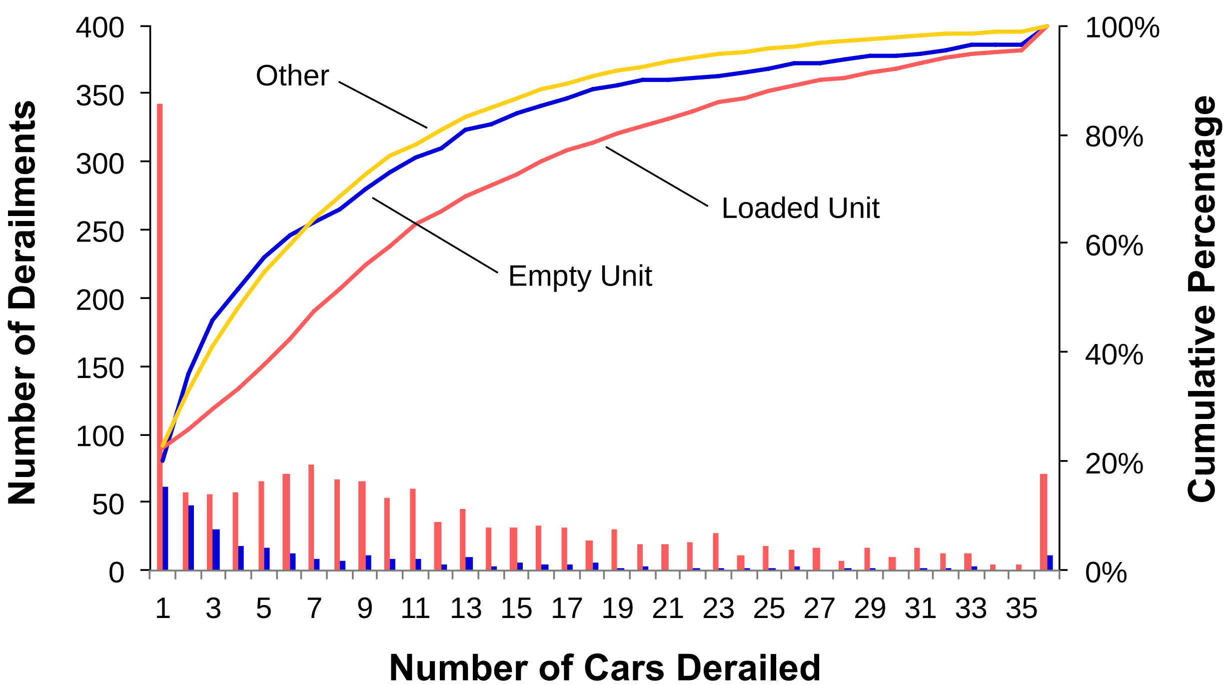


Figure 2.3: Distribution of Derailment Severity for Loaded and Empty Unit, and Other Trains

Causal Analysis

ADL Accident Cause Group Comparison

The FRA provides a detailed list of accident causes and associated cause codes for railroads to use when reporting accidents to the REA database (FRA, 2011; FRA, 2017). FRA organizes its cause codes into a hierarchical structure of related groups of causes. Arthur D. Little (ADL) Inc. worked with the Association of American Railroads (AAR) in the early 1990s to develop a variant of the FRA grouping based on input from railroad engineering and mechanical experts (ADL, 1996). The objective of the ADL grouping was to better link causes that could be addressed through similar or related preventative measures. Each FRA cause code maps to a unique ADL cause group. The first step in the causal analysis was to identify the top ten ADL cause groups for the two loading conditions and rank them by the number of derailments (Table 2.2). The cause groups shared by both are shown in bold.

Table 2.2: Frequency and Severity of the Top 10 Cause Groups* for (a) Loaded and (b) Empty Unit Train Derailments

(a) Loaded Unit Trains

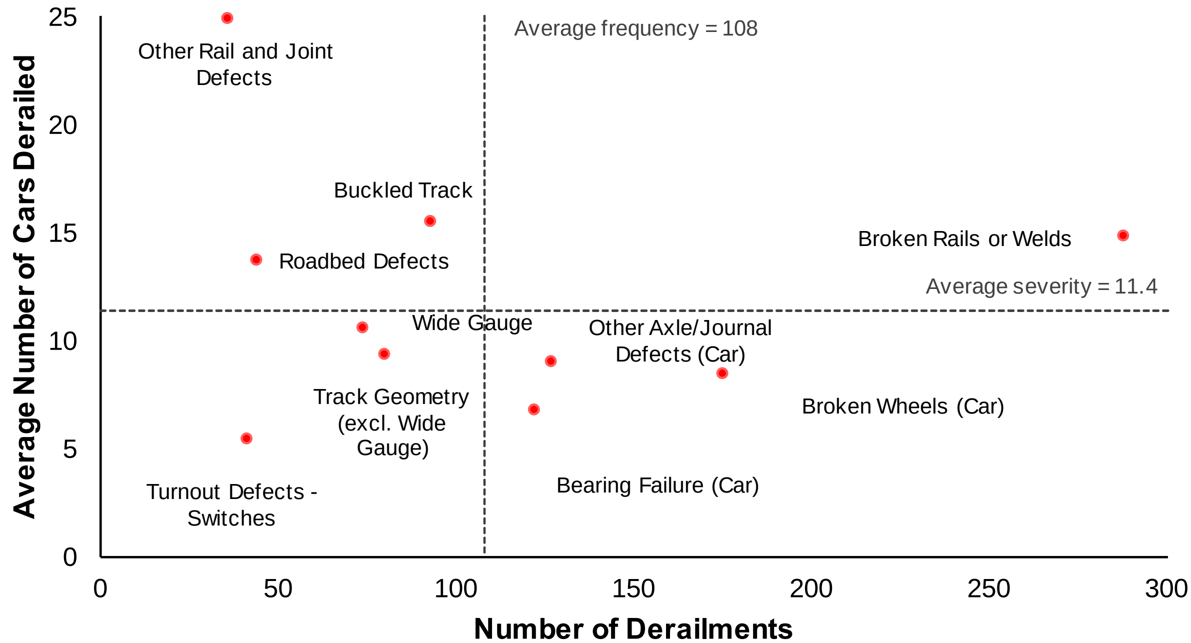
Rank	ADL Cause Group	Number of derailments	Percentage	Average Number of Cars Derailed
1	**Broken Rails or Welds**	288	18.8%	14.7
2	Broken Wheels (Car)	175	11.4%	8.3
3	Other Axle/Journal Defects (Car)	127	8.3%	8.9
4	Bearing Failure (Car)	122	7.9%	6.7
5	**Buckled Track**	93	6.1%	15.4
6	**Track Geometry (excl. Wide Gauge)**	80	5.2%	9.2
7	Wide Gauge	74	4.8%	10.5
8	Roadbed Defects	44	2.9%	13.7
9	Turnout Defects - Switches	41	2.7%	5.4
10	Other Rail and Joint Defects	36	2.3%	24.9

(b) Empty Unit Trains

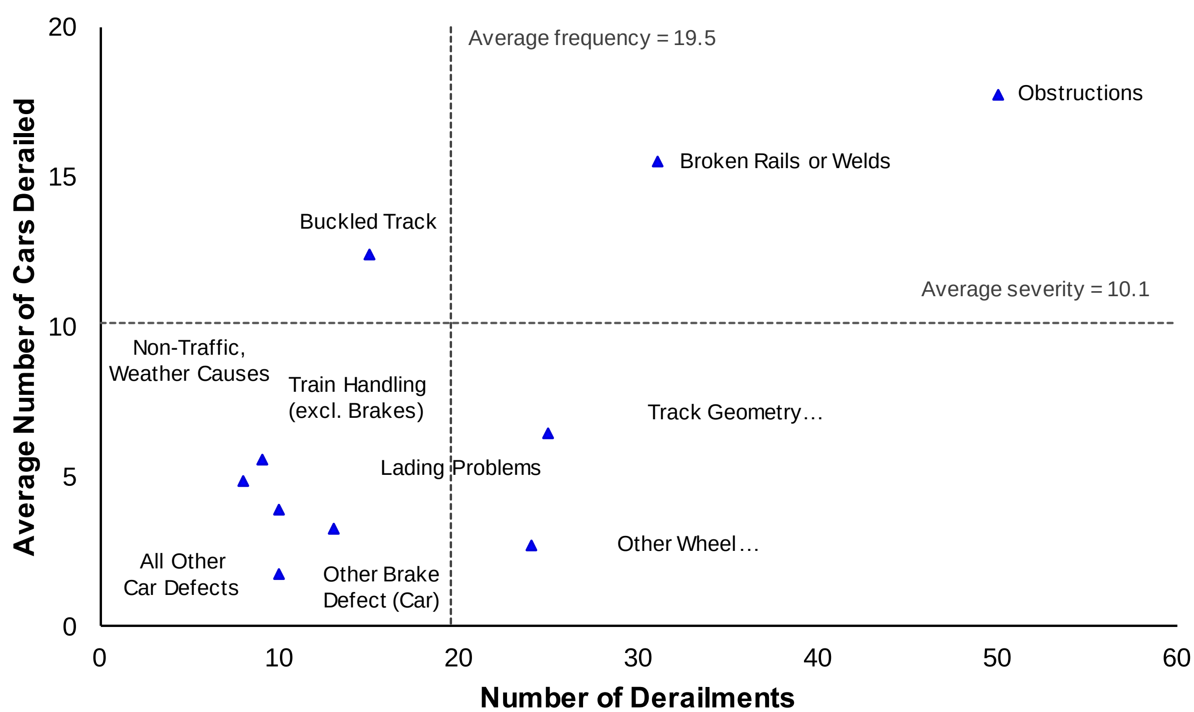
Rank	ADL Cause Group	Number of derailments	Percentage	Average Number of Cars Derailed
1	Obstructions	50	16.5%	17.8
2	**Broken Rails or Welds**	31	10.2%	15.5
3	**Track Geometry (excl. Wide Gauge)**	25	8.3%	6.4
4	Other Wheel Defects (Car)	24	7.9%	2.8
5	**Buckled Track**	15	5.0%	12.5
6	Lading Problems	13	4.3%	3.3
7	Other Brake Defect (Car)	10	3.3%	1.8
8	All Other Car Defects	10	3.3%	3.9
9	Train Handling (excl. Brakes)	9	3.0%	5.6
10	Non-Traffic, Weather Causes	8	2.6%	4.9

* Cause groups found in both unit train loading conditions shown in bold

The top ten cause groups for the two loading conditions were plotted on a frequency versus severity graph (Figure 2.4). The graph is divided into four quadrants by the average frequency and average severity of the top ten derailment cause groups. The most frequent and severe causes fall in the upper right quadrant; cause groups in this quadrant have both above-average severity and above-average frequency (Barkan et al., 2003; Dick et al., 2003; Liu et al., 2013b). The top ten derailment cause groups for loaded and empty unit trains have different distributions (Table 2.2, Figure 2.4). For loaded unit trains, broken rails or welds was the leading cause group in terms of both frequency and severity. This cause group accounted for about 20% of loaded unit train derailments with an average of about 15 cars derailing per accident. Broken rails or welds was the second leading cause of empty unit train derailments; however, obstructions accounted for the largest percentage of empty unit train derailments at 16.5% and also had the highest number of cars derailed with 18 cars on average. The obstructions cause group includes extreme environmental condition, which will be further discussed below. Cause groups shared between the two loading conditions included broken rails or welds, track geometry excluding wide gauge, and buckled track.



(a)



(b)

Figure 2.4: Frequency Versus Severity Graphs for the Top 10 Cause Groups for (a) Loaded and (b) Empty Unit Train Derailments

As mentioned above, there was a five-fold difference in the number of derailment accidents for loaded versus empty unit trains. To facilitate comparison, the number of derailments due to each cause group was normalized by the total number of derailments for each loading condition to calculate a percentage (Figure 2.5). The lines dividing the quadrants are the averages for severity and percentage of derailments for the top ten derailment cause groups for both loading conditions combined. The labels for the three cause groups shared by both loading conditions – broken rails or welds, buckled track, and track geometry (excl. wide gauge) – are highlighted in yellow and shown in bold italic. Figure 2.5 enables comparison of the relative frequency and severity of derailment cause groups under the two loading conditions. For example, derailments caused by track geometry excluding wide gauge resulted in derailments with similar severity for both loading conditions; however, this cause group accounted for a greater percentage of empty unit train derailments.

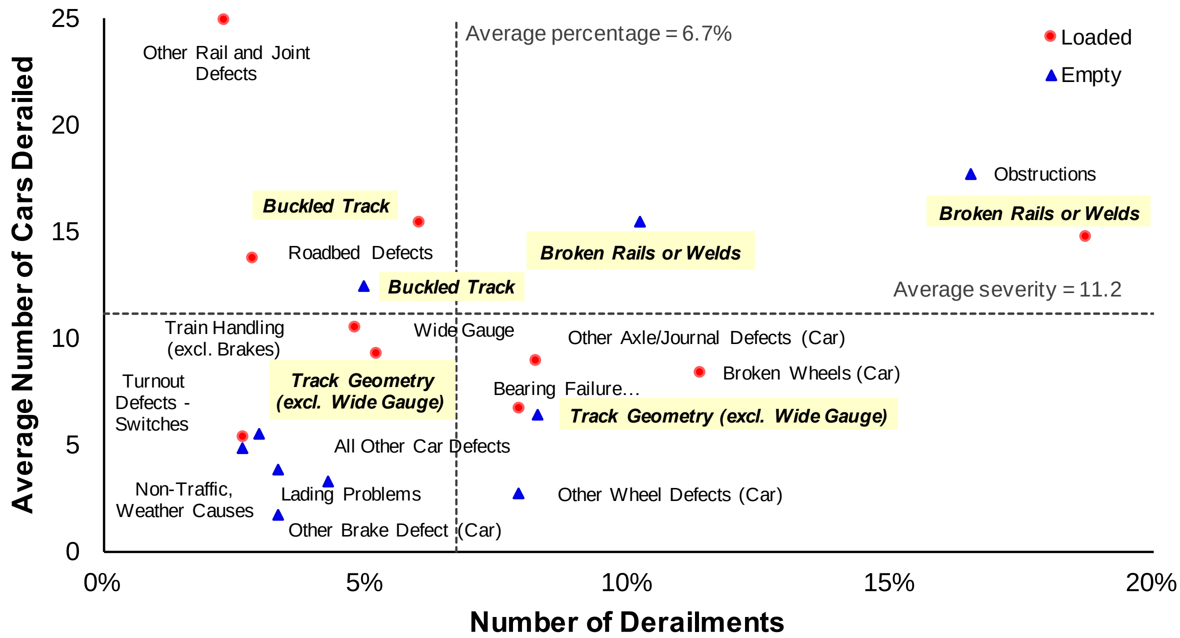


Figure 2.5: Relative Frequency Versus Severity for the Top 10 Cause Groups for Loaded and Empty Unit Train Derailments

To further understand the top causes for loaded and empty unit train derailments, they were analyzed in more detail. Specifically, loaded unit train derailments due to broken rails or welds, and empty unit train derailments due to obstructions were broken down by their individual FRA cause codes (Table 2.3). 66% of loaded unit train derailments caused by broken rails or welds were due to just two FRA cause codes: detail fracture and transverse/compound fissure. In comparison, about 70% of empty unit train derailments caused by “obstructions” were due to extreme environmental conditions, and most of these were due to just two FRA cause codes: extreme wind velocity and tornado. Tornados were also the cause of the most severe accidents, derailing 52 cars on average in each of the five events recorded.

Table 2.3: Frequency and Severity of the Top FRA Cause Codes for (a) Loaded and (b) Empty Unit Train Derailments

(a) Loaded Unit Train Derailments Caused by Broken Rails or Welds

Rank	FRA Cause	Number of derailments	Percentage	Average Number of Cars Derailed
1	Detail fracture from shelling or head check	95	33.0%	16.4
1	Transverse/compound fissure	95	33.0%	14.2
3	Vertical split head	28	9.7%	12.1
4	Weld (field)	24	8.3%	15.9
5	Head and web separation (outside joint bar limits)	21	7.3%	10.1
6	Base	14	4.9%	17.3
7	Engine burn fracture	4	1.4%	13.8
8	Horizontal split head	4	1.4%	14.3
9	Piped rail	2	0.7%	9.5
10	Weld (plant)	1	0.3%	23.0

(b) Empty Unit Train Derailments Caused by Obstructions

Rank	FRA Cause	Number of derailments	Percentage	Average Number of Cars Derailed
1	Extreme environmental condition - Extreme wind velocity	27	54.0%	19.9
2	Snow, ice, mud, gravel, coal, sand, etc. on track	11	22.0%	3.0
3	Extreme environmental condition - Tornado	5	10.0%	52.0
4	Object or equipment on or fouling track (other than above)	4	8.0%	6.3
5	Extreme environmental condition - Flood	2	4.0%	10.0
6	Other extreme environmental conditions	1	2.0%	15.0

Top Ten Causes on Mainline and Siding Tracks

The data used in this study included derailments on both mainline and siding tracks. There were 1,426 (93%) derailments of loaded unit trains on mainlines and 110 (7%) on sidings. For empty trains, 275 (91%) occurred on mainline tracks, and 28 (9%) were on sidings. A question of interest was whether these two types of track differed in their distribution of derailment causes. For example, sidings might have a higher percentage of switch-related derailments due to the greater relative frequency of turnouts on siding tracks compared to mainlines. Conversely, the higher operating speeds of mainline tracks might result in a higher percentage of derailments due to equipment causes (Liu et al., 2012). There were insufficient empty unit train derailments for a meaningful comparison of their distributions so the comparison of mainline and siding track accident causes was limited to loaded unit trains only. The top ten cause groups for these trains were ranked by number of derailments on each type of track (Table 2.4).

Among the top ten, broken rails or welds, wide gauge, track geometry excluding wide gauge, and buckled track were common to both mainline and siding tracks, indicated in bold in Table 2.4. As suggested above, three of the top ten cause groups for derailments on siding tracks were switch related, accounting for about 20% of the total, whereas none of the top ten mainline cause groups were switch related. Also as suggested, four of the top ten cause groups on mainline tracks were equipment related, accounting for 32% of the total, while on sidings only one cause group was equipment related accounting for less than 3%.

Table 2.4: Frequency and Severity of the Top Ten Derailment Cause Groups* for Loaded Unit Train Derailments on (a) Mainline Track and (b) Siding Track

(a) Mainline Track

Rank	ADL Cause Group	Number of Derailments	Percentage	Average Number of Cars Derailed
1	**Broken Rails or Welds**	262	18.4%	15.2
2	Broken Wheels (Car)	174	12.2%	8.3
3	Other Axle/Journal Defects (Car)	126	8.8%	8.9
4	Bearing Failure (Car)	121	8.5%	6.8
5	**Buckled Track**	90	6.3%	15.5
6	**Track Geometry (excl. Wide Gauge)**	72	5.0%	9.7
7	**Wide Gauge**	53	3.7%	11.6
8	Roadbed Defects	42	2.9%	13.9
9	Coupler Defects (Car)	36	2.5%	7.4
10	Other Rail and Joint Defects	34	2.4%	25.9

(b) Siding Track

Rank	ADL Cause Group	Number of Derailments	Percentage	Average Number of Cars Derailed
1	**Broken Rails or Welds**	26	23.6%	9.8
2	**Wide Gauge**	21	19.1%	7.8
3	Turnout Defects - Switches	12	10.9%	5.1
4	**Track Geometry (excl. Wide Gauge)**	8	7.3%	4.8
5	Switching Rules	6	5.5%	4.2
6	Use of Switches	4	3.6%	3.5
7	All Other Car Defects	3	2.7%	5.3
8	**Buckled Track**	3	2.7%	11.3
9	Joint Bar Defects	3	2.7%	7.7
10	Misc. Track and Structure Defects	2	1.8%	6.0

* Cause groups found in both types of track shown in bold

Discussion and Future Research

The differing frequency of loaded versus empty unit train derailments recorded in the FRA REA database might suggest a difference in the derailment rate for the two loading conditions, or it may simply indicate that fully loaded unit trains accrue more mileage, and therefore more exposure to potential derailment circumstances than empty unit trains. The latter is unlikely to be the case for "shuttle" trains that travel back and forth as a unit between the same origin and destination for loading and unloading. However, there are other types of unit-train-like operations in which cars travel together while loaded, but after they reach their destination and are unloaded, the empty cars may not remain together, or even return to the same origin. Overall, railcars travel about 40% more car-miles while loaded than empty (AAR, 2015); however, this difference by itself is not enough to account for the possible difference in exposure mentioned above. Consequently, specific traffic data for loaded and empty unit trains are needed to address the effect of loading condition on derailment rate. It is plausible that some derailment causes are influenced by the greater weight of a loaded rail vehicle. Such causes could include failure of certain railcar components or elements of the track structure it is traveling over. In general, these component failures would be expected to occur irrespective of a car's placement in a unit train. FRA regulations, AAR interchange standards, American Railway Engineering and Maintenance-of-Way Association recommended practices, and the track design, maintenance, and inspection standards of individual railroads are all intended to prevent such failures. It is hoped that the results presented here will provide insight into the failure modes associated with loaded and empty unit train operation and inform research on the most effective means of preventing these failures and managing the risk.

Conclusions

The use of unit trains has expanded substantially over the past half century due to the substantial improvements in economies of scale, equipment utilization, operating efficiencies, and transit times that they offer when transporting bulk commodities such as coal and grain. Over the past decade and a half, growth in domestic production of flammable liquids has led to expanded rail transport of these products in unit trains as well. This has led to increased interest in the factors affecting the safety performance of unit trains. Limited previous research has considered the relationship between the loading condition of unit trains and associated derailment causes. In this study, a methodology was developed to classify loaded and empty unit trains using the FRA REA database. The resultant dataset enabled analysis of a number of questions not previously investigated that provides new insights about the factors affecting unit train safety. Over the fifteen-year period, the frequency of derailments for both loading conditions declined more than 50% while the average derailment severity for both loading conditions fluctuated but showed no particular trend. Approximately five times more loaded unit train derailments were recorded in the REA database than empty unit trains but in the absence of specific unit train traffic data, inferences about differences in derailment rates are not possible. Loaded unit trains were more than four times heavier than empty unit trains, and loaded train derailments tended to involve more cars than empty trains. The distribution of derailment causes also differed, with broken rails or welds being the leading cause group for loaded unit trains, and obstructions, including extreme environmental conditions such as extreme wind velocity, being the leading cause group for empty unit trains. Over 90% of the derailments of loaded and empty unit trains considered in this study occurred on mainline tracks, and the distribution of causes differed between mainline and siding tracks.

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CHAPTER 3: COMPARATIVE RISK OF TRANSPORTING HAZARDOUS MATERIALS BY UNIT TRAIN AND MANIFEST TRAIN

Introduction

Over the past decade, unit-train transport of tank cars carrying hazardous materials, especially flammable liquids, has increased substantially. This is due to the greater efficiencies afforded by unit trains through reductions in operating expenses, bulk loading, and other economies of scale (Grimes, 1981; Grimes, 1982; Starr, 1976). While unit trains are efficient at transporting large quantities of a single commodity, if that commodity is hazardous, they also introduce the possibility of larger derailments and spills of these materials. Conversely, transportation in manifest trains requires more trains and thus increases the potential for exposure to a possible derailment. Given these trade-offs, it is important to understand the relative risks associated with transporting hazardous materials in these different types of trains.

There has only been limited research comparing these risks (Liu, 2017). In this chapter, I use a risk analysis model to quantify both the likelihood and consequence of transporting hazardous materials using unit trains and manifest trains in two different tank car specifications, DOT 111s and DOT 117s. The metrics used to assess consequences are the number of tank cars derailed, the number of tank cars releasing, and the quantity released. The goal is to develop a methodology and the insight needed to quantify the risk associated with different train configurations and tank car specifications to inform risk-management decision-making for transport of hazardous materials.

Literature Review

To understand the effect of train configurations on risk, Liu (2017) developed a risk analysis model to quantify the risk associated with a release and investigated different scenarios of tank car positions that generate the highest and the lowest risk, along with random tank car positioning for comparison. He found that if tank cars are positioned to give the lowest risk, i.e., placing them in the back of the train, transporting hazardous materials in manifest trains reduces the probability of a release incident compared to transporting them in unit trains; and if the tank cars are positioned at random or positioned to give the highest risk, the probability of release is higher for manifest trains compared to unit trains.

Operationally, cars are frequently positioned in groups if they have destinations in common. However, without knowing the destinations and the positions of different groups, random placement of tank cars in a train consist is more realistic, so that was how car placement was considered in this analysis. In addition to investigating the probability of releases, this paper also quantifies the severity of incidents in terms of the number of tank cars derailed, the number of tank cars releasing, and the quantity released. To quantify the risk, the Multiple Tank Car Release (MTCR) model described by Liu et al. (2014) was used.

Methodology

There are two components to risk, probability and consequence. In this chapter, risk refers to the product of the probability and consequence. The probability was estimated using the MTCR model, and the consequence was estimated using the Expected Quantity Released (EQR) model. The MTCR model calculates the distribution of tank cars derailed and tank cars releasing by calculating the distribution for each of a series of variables. The MTCR model follows a logical sequence of events beginning with a train derailment, followed by cars derailed, tank cars derailed, and tank cars releasing (Figure 3.1). The main inputs for the MTCR model are train characteristics, track characteristics and tank car conditional probability of release. Details for this part of the model can be found in Liu et al. (2014). The distribution it produces is summarized in the following equation:

$$P(X_R) \approx \sum_{X_D=0} \left\{ P(X_R|X_D) \left\{ \sum_{X=0} P(X_D|X) \left[\sum_{K=1} P(X|K) POD(K) \right] \right\} \right\}$$

where:

K = point of derailment (POD) (position of first car derailed)

POD(K) = probability distribution of point of derailment

X = number of cars (tank cars and non-tank cars) derailed

P(X|K) = probability distribution of number of cars derailed given point of derailment

X_D = number of tank cars derailed

$P(X_D|X)$ = probability distribution of tank cars derailed given total number of cars derailed

X_R = number of tank cars releasing

$P(X_R|X_D)$ = probability distribution of tank cars releasing given number of tank cars derailed

$P(X_R)$ = probability of X_R number of tank cars releasing per train trip on a route

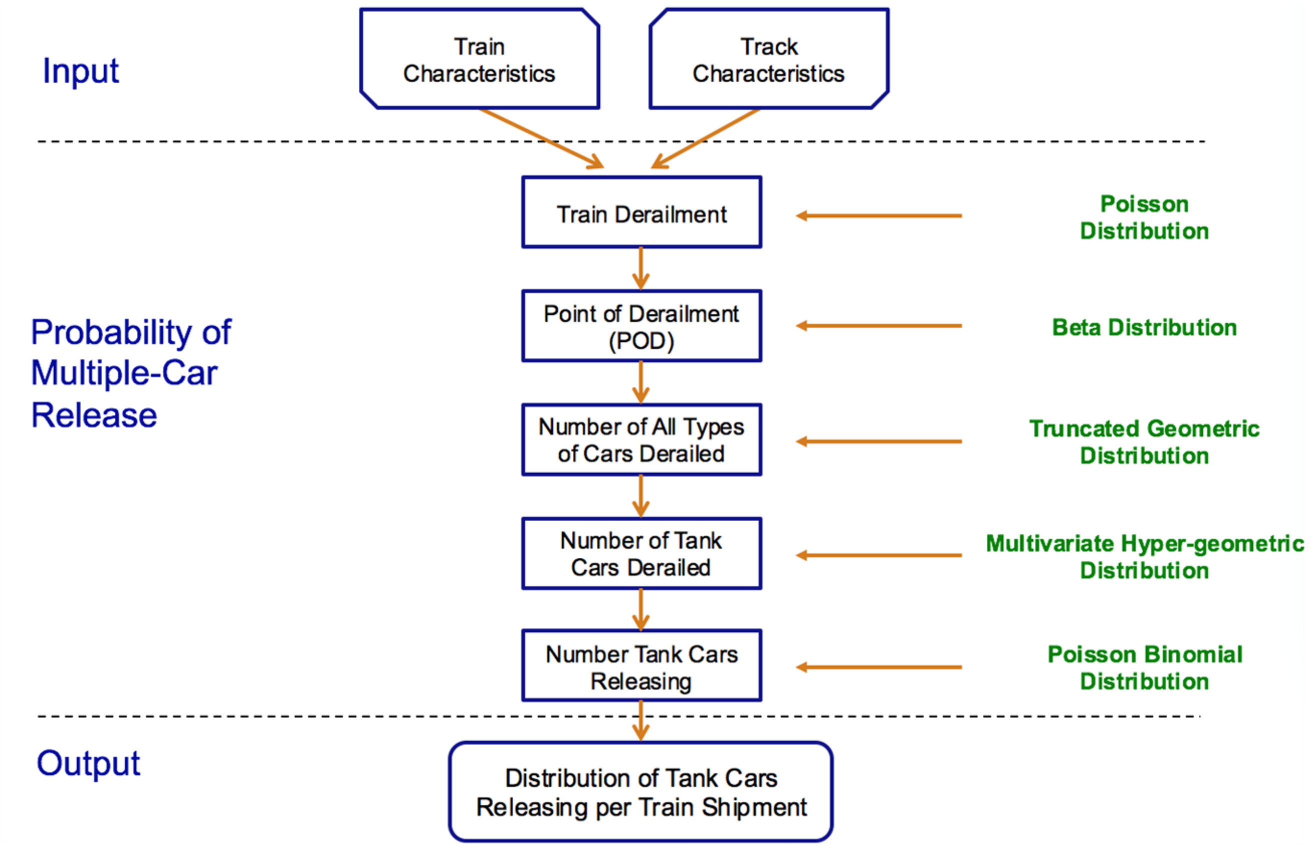


Figure 3.1: Flow Chart of the MTCR Model (Modified from Liu et al., 2014)

After the MTCR model produced the distribution of tank cars releasing, the distribution of quantity released was calculated using the EQR model. The model was developed based on statistics developed by the Railway Supply Institute (RSI) – Association of American Railroads (AAR), Railroad Tank Car Safety Research and Test Project that estimated probability distributions of quantity lost from tank cars in accidents (Treichel et al, 2006). The lading lost from each tank car is divided into five levels with the corresponding probabilities (Table 3.1). The tank car capacity was assumed to be 30,000 and 31,800 gallons for crude oil transported by DOT 111 and DOT 117 tank cars respectively (AFPM, 2014). Based on the average percentage of quantity released for each level, the quantity released in gallons can be calculated. The EQR model assumes that the quantity released for each tank car is independent of other cars in the train. Thus, a one-car release has five outcomes, and a twenty-car release will have five to the power of twenty combinations of outcomes.

Table 3.1: Lading Loss Categories

Quantity Released (QR)	Average QR	Probability
0%-5%	2.5%	0.193
5%-20%	12.5%	0.092
20%-50%	35.0%	0.139
50%-80%	65.0%	0.128
80%-100%	90.0%	0.447

To compare the risk associated with unit trains and manifest trains, four scenarios were used to transport 20 tank cars of petroleum crude oil per day for the same distance over a one-year period as follows: one unit train of 100 tank cars every five days, or more frequent manifest trains with 50, 20 and 10 tank cars operating every two, one, and one-half days, respectively. In all scenarios, train length was standardized to control for train characteristics. The length of all trains was held constant at 102 cars plus four locomotives, which is a typical length for unit trains on Class I railroads (Chapter 2 and Li et al., 2018). The number of annual tank-car miles was constant, but the number of trains varied, with manifest trains requiring more annual trips (Table 3.2). These scenarios were studied with two tank car specifications: conventional, non-jacketed US DOT 111 and DOT 117. The gross rail load (GRL) of fully loaded DOT 111 tank cars and other cars was assumed to be 131.5 tons; and the GRL of DOT 117 tank cars was assumed to be 143 tons (FRA, 2011).

Table 3.2: Train Characteristics

Train Characteristics	Unit Train	Non Unit Train 50	Non Unit Train 20	Non Unit Train 10
Train length	106	106	106	106
-Number of tank cars	100	50	20	10
-Number of other cars	2	52	82	92
Number of trains per year	73	146	365	730

All trains travelled on the same hypothetical route with the following characteristics: 100 miles long, signaled, and annual traffic greater than 20 MGT (Table 3.3). These general characteristics are typical of many parts of the U.S. Class I railroad mainline network (Keefe, 2016, Liu et al, 2017) including many of the routes over which flammable liquids are shipped. The year of estimation used for all scenarios and tank car specifications was 2009, which was the last year of the analysis period for the comprehensive derailment rate estimates (Liu et al., 2017). The derailment rate has declined since then, so the risk estimates presented here are higher than what would be expected using current derailment rates.

In addition to train and route characteristics, the conditional probability of release (CPR) for the specific tank car designs used is an input to the MTCR model. CPR varies based on factors such as tank car specification and derailment speed. The tank car specifications used in this analysis and the average CPR for the two tank car specifications are shown in Table 3.4. All three principal inputs were used to generate distributions of the number of tank cars derailed, number of tank cars releasing, and quantity released. These metrics were used to assess the risk of transporting the same number of tank cars per year, but in different train configurations as discussed above. In addition to the tank cars of interest in this analysis, the manifest trains were assumed to transport other cars carrying various non-regulated materials. In the case of unit trains, the other cars were buffer cars, which are required by federal regulation to be placed between occupied locomotives and cars carrying hazardous materials (FRA, 2005).

Table 3.3: Hypothetical Route Characteristics

FRA Track Class	Length (Miles)	% Length
1	0	0%
2	5	5%
3	15	15%
4	80	80%
5	0.0	0.0%

Method of Operation	Length	% Length
Signaled	100	100%
Dark	0	0%

Annual Traffic	Length	% Length
>20 MGT	100	100%
<20 MGT	0	0%

Table 3.4: Tank Car Specifications and Conditional Probability of Release (CPR)

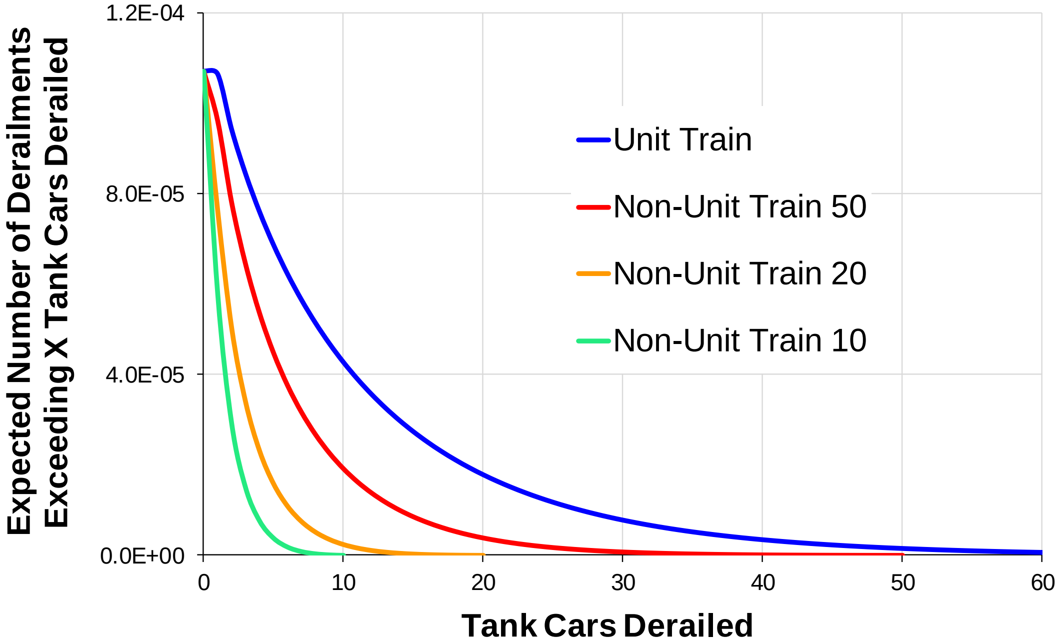
Tank Car Specification	Head Thickness (inches)	Shell Thickness (inches)	Jacket	Head Shield	Shell Inside Diameter (Inches)	CPR	Percent Reduction in CPR
DOT 111	0.4375	0.4375	No	No	119	0.239	
DOT 117	0.5625	0.5625	Yes	Full	116.75	0.035	85%

Results

Number of Tank Cars Derailed

Results from the MTCR model can be represented in different ways. An inverse cumulative distribution was used, in which the value on the x-axis is the number of derailed tank cars, and the value on the y-axis is the expected number of derailments with greater than or equal to the corresponding value on the x-axis (Figures 3.2 and 3.3). The MTCR model was used for each tank car specification, DOT 111 (Figures 3.2a and 3.3a) and DOT 117 (Figures 3.2b and 3.3b). For example, in Figure 3.2a, the expected number of derailments of unit trains where 20 or more tank cars derailed is about 2.0E-05. As mentioned above, the DOT 117 has a higher GRL than the DOT 111 and other cars in the trains simulated. Using a ton-mile based derailment rate, the heavier the train, the higher the derailment rate. Unit trains of DOT 117s are all higher GRL cars, so the derailment rate in Figure 3.2b is slightly higher than in Figure 3.2a and other scenarios.

Unit trains have a greater risk of a high consequence derailment because they have more tank cars per train than the other scenarios. That is why the per-trip curve of the unit train is higher than others in Figure 3.2. On the other hand, tank cars traveling in unit trains have a lower likelihood of being in a train that derails because fewer trains are required to move the same volume and therefore these tank cars have less exposure to derailments. A unit train has a lower expected number of small derailments, but the distribution also has a longer, higher tail, meaning that the expected number of larger derailments is higher (Figure 3.3). The effect of the weight difference on the annual expected number of derailments for DOT 111 and DOT 117 was minimal when comparing Figure 3.3a to Figure 3.3b. To facilitate the comparison of these distributions, summary statistics are presented in Table 3.5.



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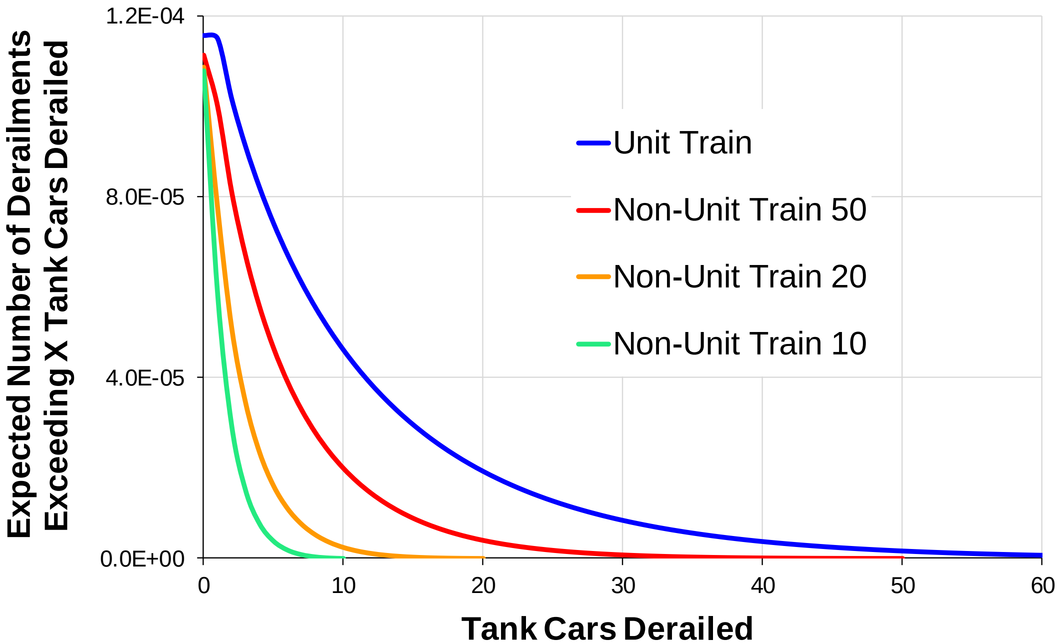
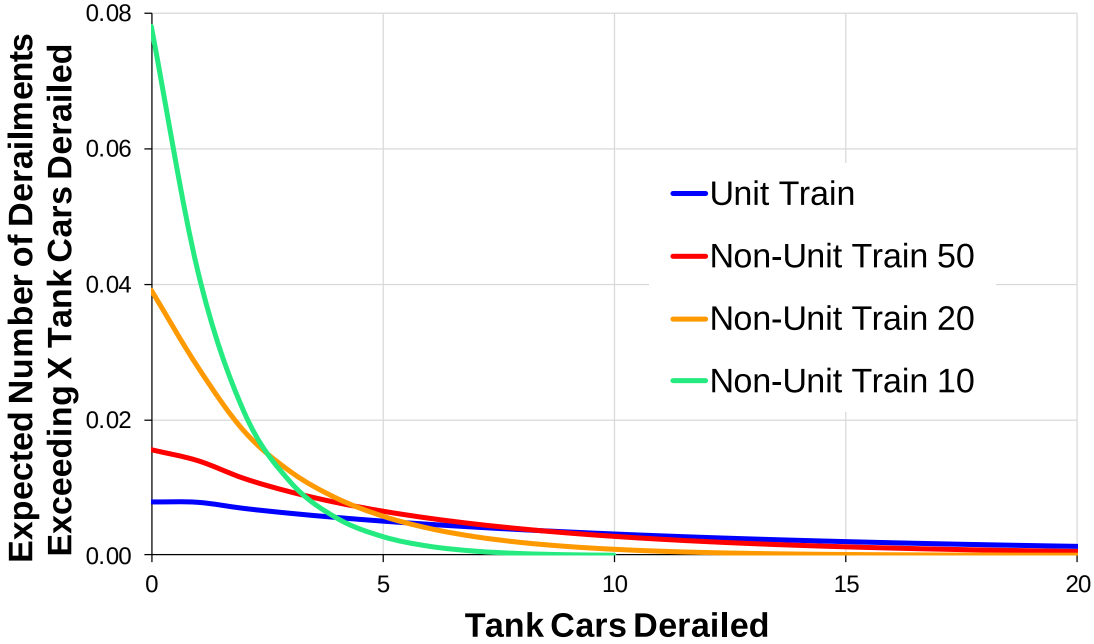


(b)

Figure 3.2: Inverse Cumulative Distribution of Derailment Incidents per Train Trip by Number of Tank Cars Derailed for (a) DOT 111 Tank Cars and (b) DOT 117 Tank Cars



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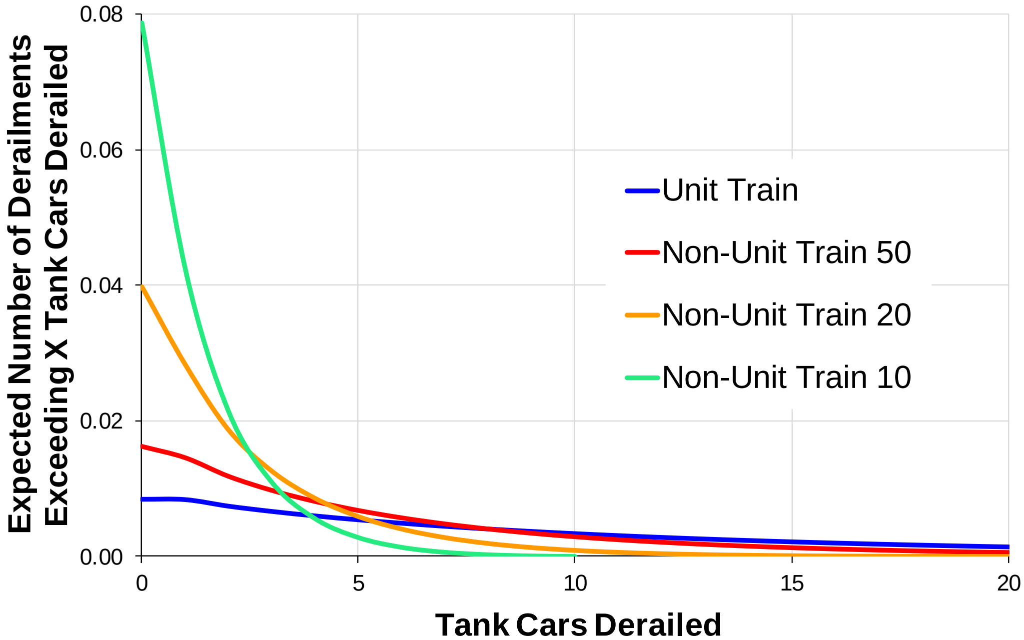


(b)

Figure 3.3: Inverse Cumulative Distribution of Annual Expected Number of Derailments by Number of Tank Cars Derailed for (a) DOT 111 Tank Cars and (b) DOT 117 Tank Cars

Table 3.5: Summary Statistics for Distributions of Number of Tank Cars Derailed

Expected Number of Derailments

		Unit Train	Non-Unit Train 50	Non-Unit Train 20	Non-Unit Train 10
DOT 111	Per Trip	0.0001	0.0001	0.0001	0.0001
	Per Year	0.008	0.016	0.039	0.078
DOT 117	Per Trip	0.0001	0.0001	0.0001	0.0001
	Per Year	0.008	0.016	0.040	0.079

Expected Number of Tank Cars Derailed per Trip

		Unit Train	Non-Unit Train 50	Non-Unit Train 20	Non-Unit Train 10
DOT 111	Expected Value	0.0012	0.0006	0.0002	0.0001
	Variance	0.027	0.007	0.001	0.000
DOT 117	Expected Value	0.0013	0.0006	0.0002	0.0001
	Variance	0.029	0.007	0.001	0.000

Expected Annual Number of Tank Cars Derailed

		Unit Train	Non-Unit Train 50	Non-Unit Train 20	Non-Unit Train 10
DOT 111	Expected Value	0.085	0.085	0.085	0.085
	Variance	1.933	0.996	0.434	0.246
DOT 117	Expected Value	0.092	0.088	0.086	0.086
	Variance	2.089	1.036	0.441	0.248

The expected number of derailments per train trip for all scenarios, regardless of how many cars derailed and the tank car specifications, is about the same (Table 3.5). However, for the expected annual number of derailments, unit trains are less likely to be involved in a derailment because they make fewer trips. If the number of cars derailed is also considered, the expected number and the variance of the number of tank cars derailed per trip for unit trains is higher than other scenarios. This is due to the larger number of tank cars per unit-train consist.

The expected value for the annual number of tank cars derailed is the highest for the unit train scenario. In addition, the variance in the annual number of tank cars derailed for the unit train scenario is also the largest, indicating that the consequences are more variable, both above and below the expected value. Again, the difference in expected number of derailments between the different shipping scenarios with DOT 117 tank cars is caused by the assumed difference in GRL. Even though unit trains of DOT 117 tank cars have a slightly higher estimated likelihood of derailment, the quantity of material transported will also be larger due to their higher capacity compared to DOT 111s.

Number of Tank Cars Releasing

The distributions of the number of tank cars releasing per trip and per year were also plotted (Figures 3.4 and 3.5). Again, unit trains have a higher expected number of releases per trip with distributions higher than other scenarios. There is a trade-off between frequency and severity in annual number of tank cars releasing. Although unit trains have fewer derailments with a smaller number of tank cars releasing, they have more derailments with a large number of tank cars releasing. The summary statistics for these distributions were calculated to quantify the difference in these distributions (Table 3.6). Note that DOT 117s substantially reduce the number of tank cars releasing compared to DOT 111s.

Table 3.6: Summary Statistics for Distributions of Number of Tank Cars Releasing

Expected Number of Releases

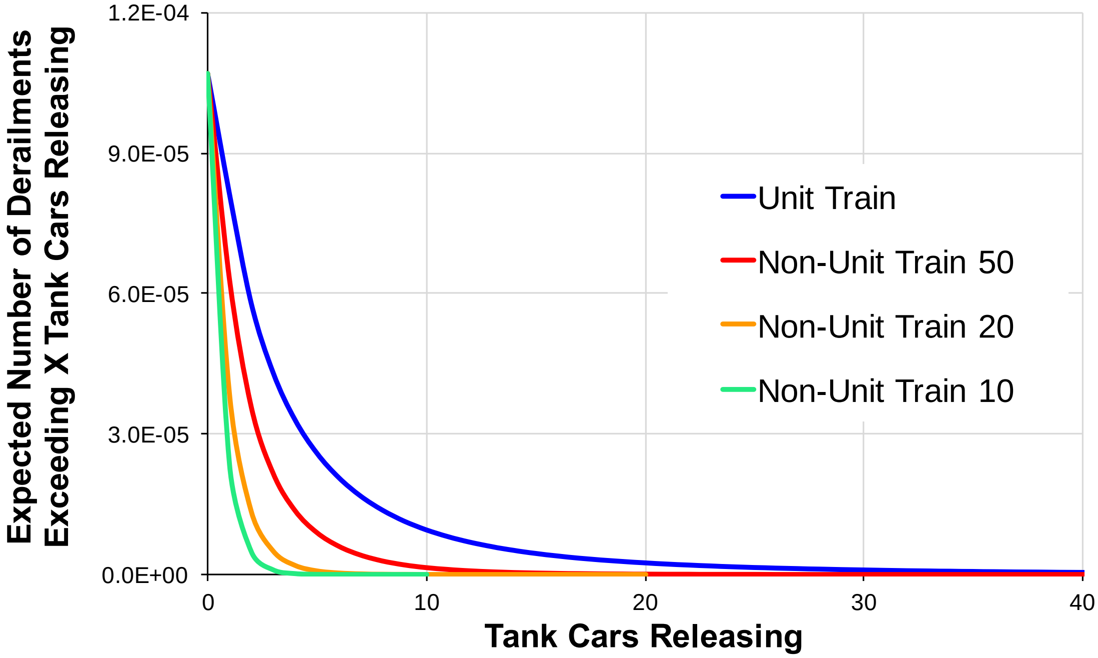
		Unit Train	Non-Unit Train 50	Non-Unit Train 20	Non-Unit Train 10
DOT 111	Per Trip	0.00008	0.00006	0.00004	0.00002
	Per Year	0.0059	0.0092	0.0140	0.0171
DOT 117	Per Trip	0.00004	0.00002	0.00001	0.00000
	Per Year	0.0028	0.0030	0.0030	0.0030

Expected Number of Tank Cars Releasing per Trip

		Unit Train	Non-Unit Train 50	Non-Unit Train 20	Non-Unit Train 10
DOT 111	Expected Value	0.00039	0.00016	0.00006	0.00003
	Variance	0.00494	0.00079	0.00013	0.00004
DOT 117	Expected Value	0.00008	0.00003	0.00001	0.00000
	Variance	0.00044	0.00005	0.00001	0.00000

Expected Annual Number of Tank Cars Releasing

		Unit Train	Non-Unit Train 50	Non-Unit Train 20	Non-Unit Train 10
DOT 111	Expected Value	0.028	0.024	0.022	0.021
	Variance	0.360	0.114	0.047	0.032
DOT 117	Expected Value	0.006	0.004	0.003	0.003
	Variance	0.032	0.007	0.004	0.003



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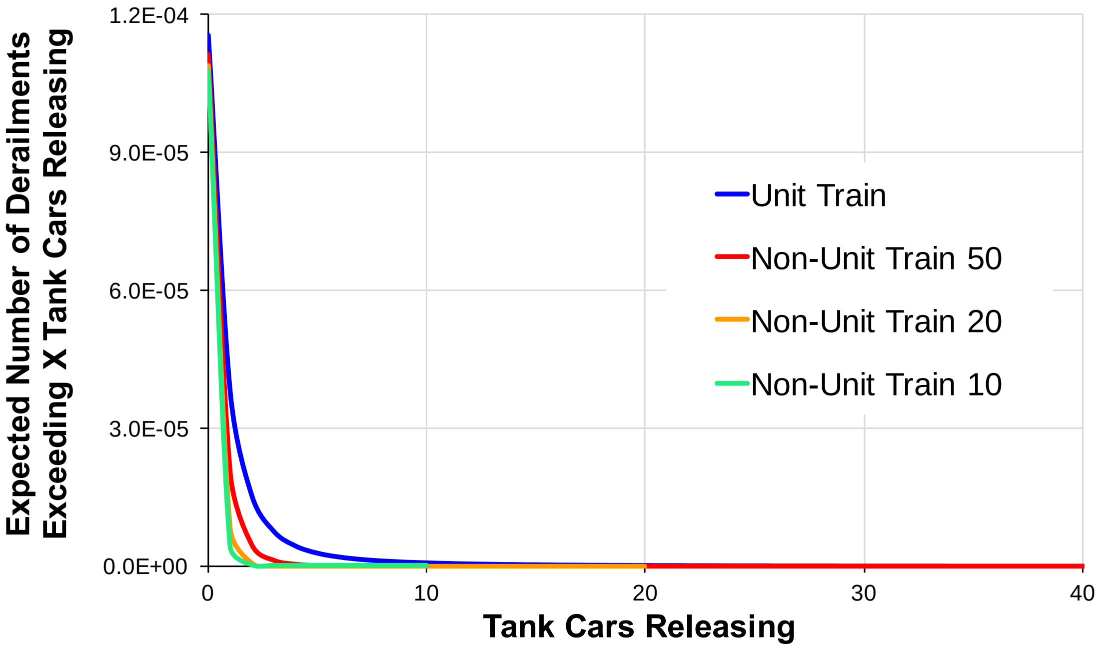
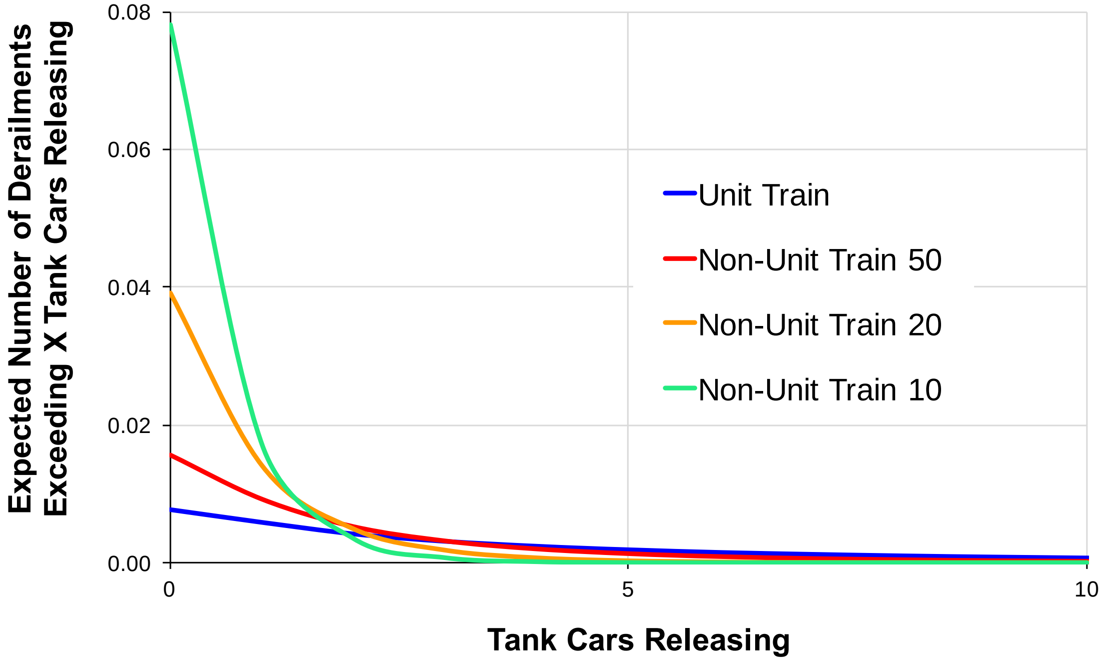


(b)

Figure 3.4: Inverse Cumulative Distribution of Derailment Incidents per Train Trip by Number of Tank Cars Releasing for (a) DOT 111 Tank Cars and (b) DOT 117 Tank Cars



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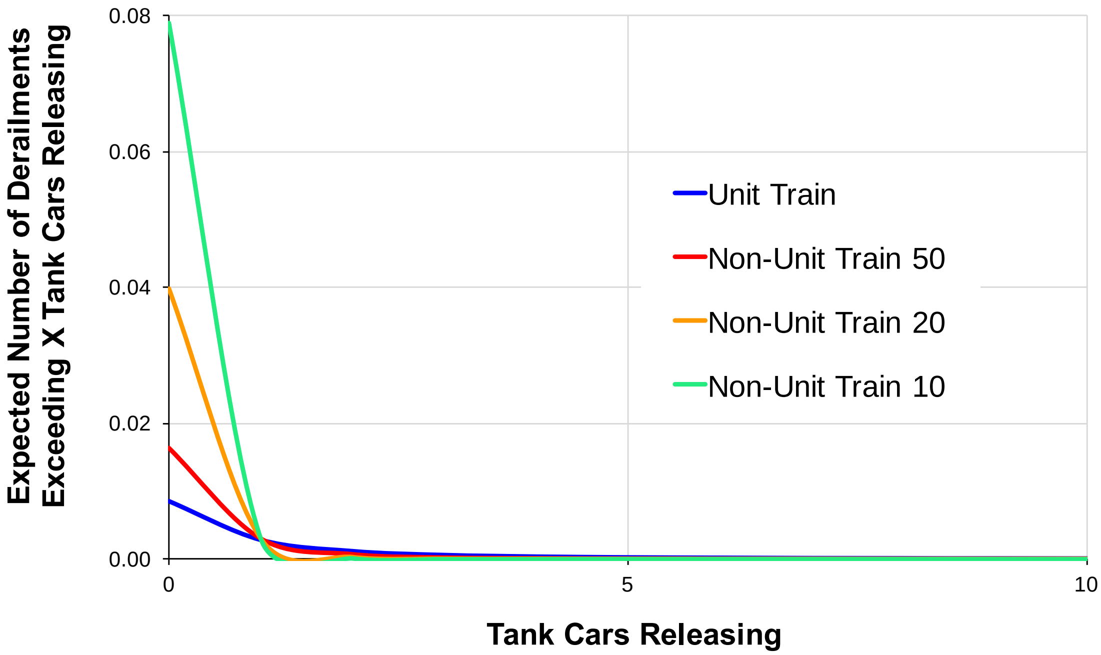
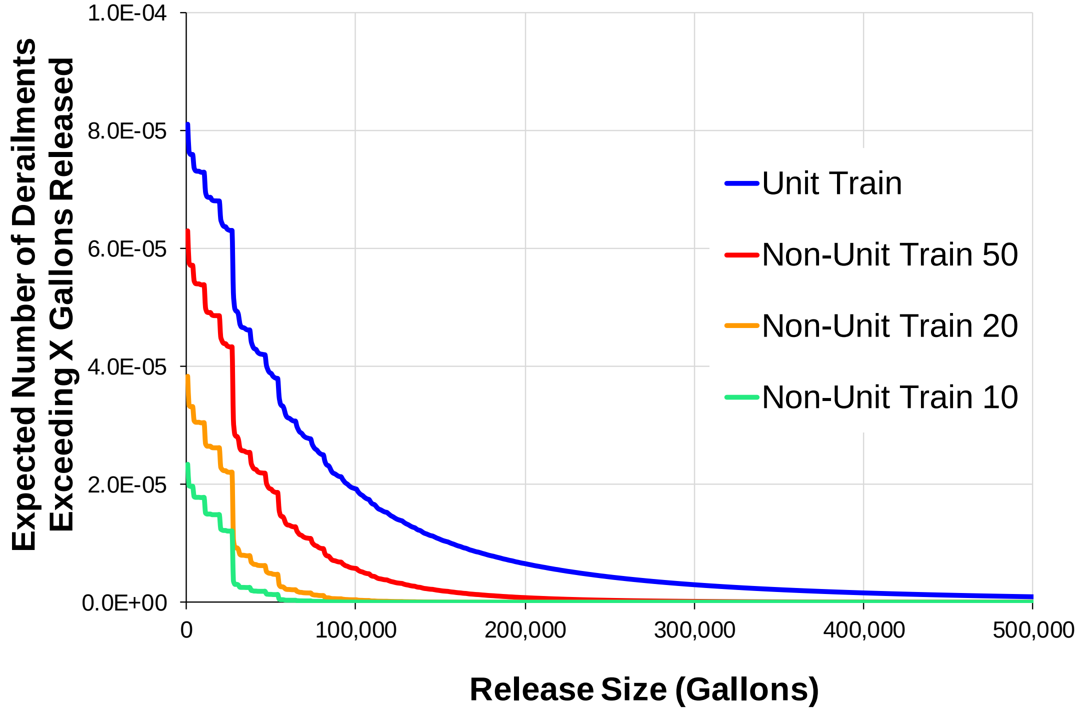


(b)

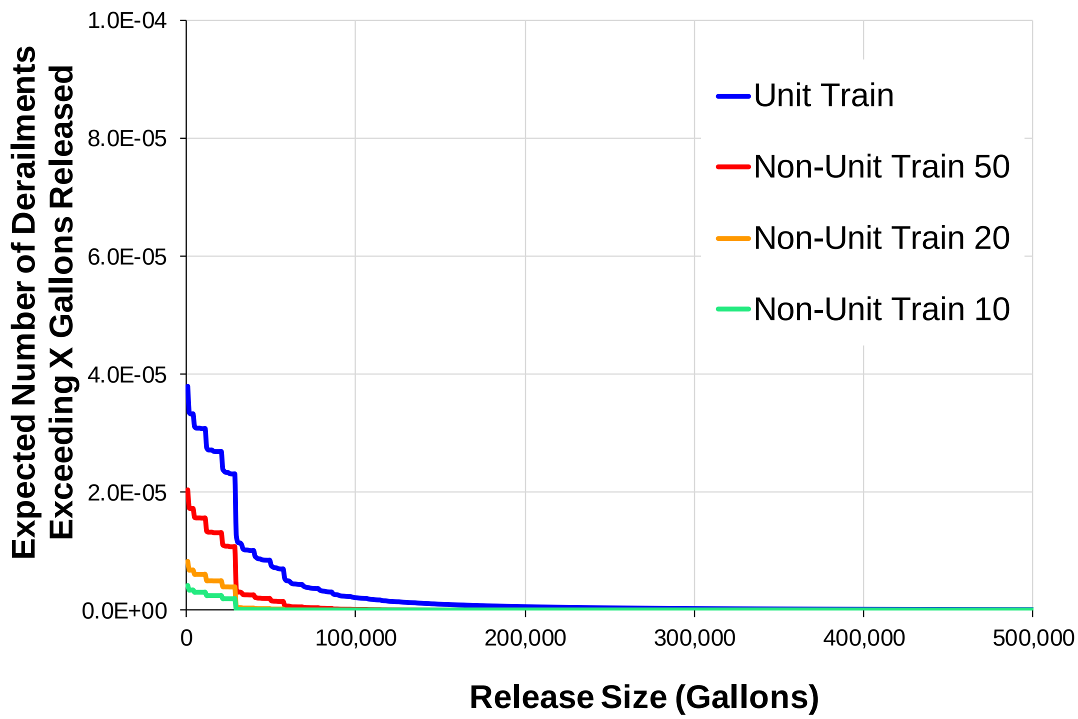
Figure 3.5: Inverse Cumulative Distribution of Annual Expected Number of Derailments by Number of Tank Cars Releasing for (a) DOT 111 Tank Cars and (b) DOT 117 Tank Cars

Expected Quantity Released

The estimated probability of release from the MTCR model was used as input to the EQR model to calculate distributions of the total quantity released (Figures 3.6 and 3.7), which provides insight into the size of release. There is a large amount of variance in the EQR output, so the distributions are clearly separated in these figures. The distribution for unit trains in Figure 3.7 is lower than the other scenarios on the left, and it crosses over the other distributions and remains above the other distributions on the right. This indicates that unit train derailments are less likely to occur, but as stated previously, they have higher potential consequences if they do. Expected quantity released per trip for unit trains is higher, and annual expected quantity released for unit trains is also higher in terms of both expected value and variance (Table 3.7). Expected quantity released is reduced by the use of DOT 117 tank cars by more than 75%.

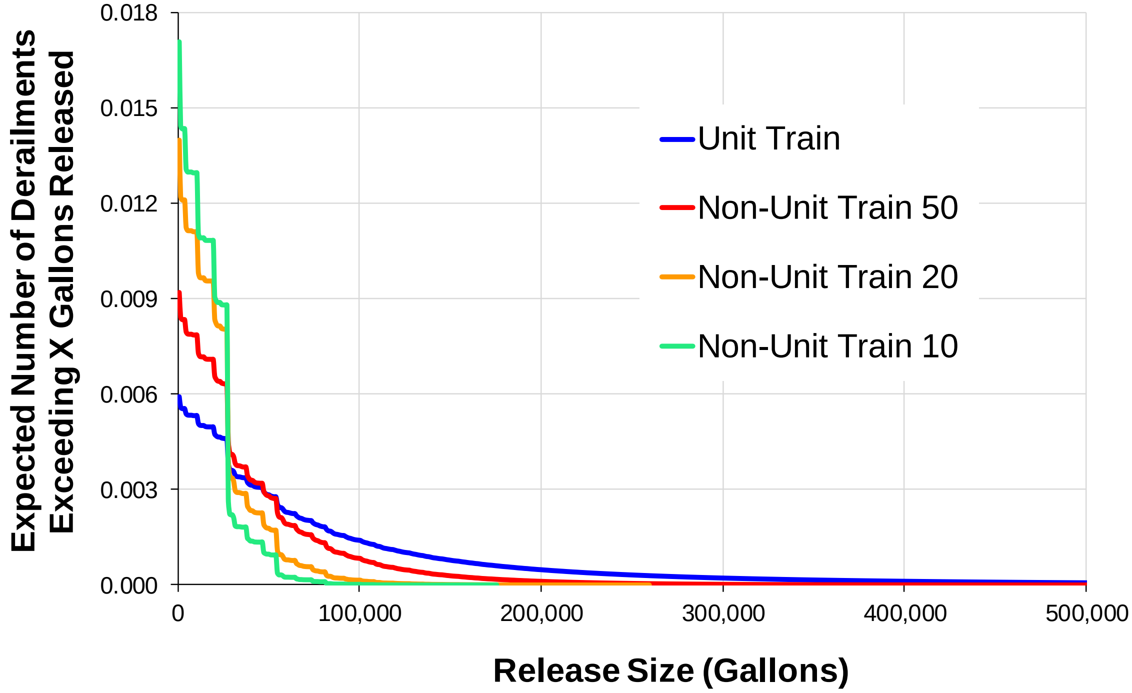


(a)



(b)

Figure 3.6: Inverse Cumulative Distribution of Derailment Incidents per Train Trip by Quantity Released for (a) DOT 111 Tank Cars and (b) DOT 117 Tank Cars



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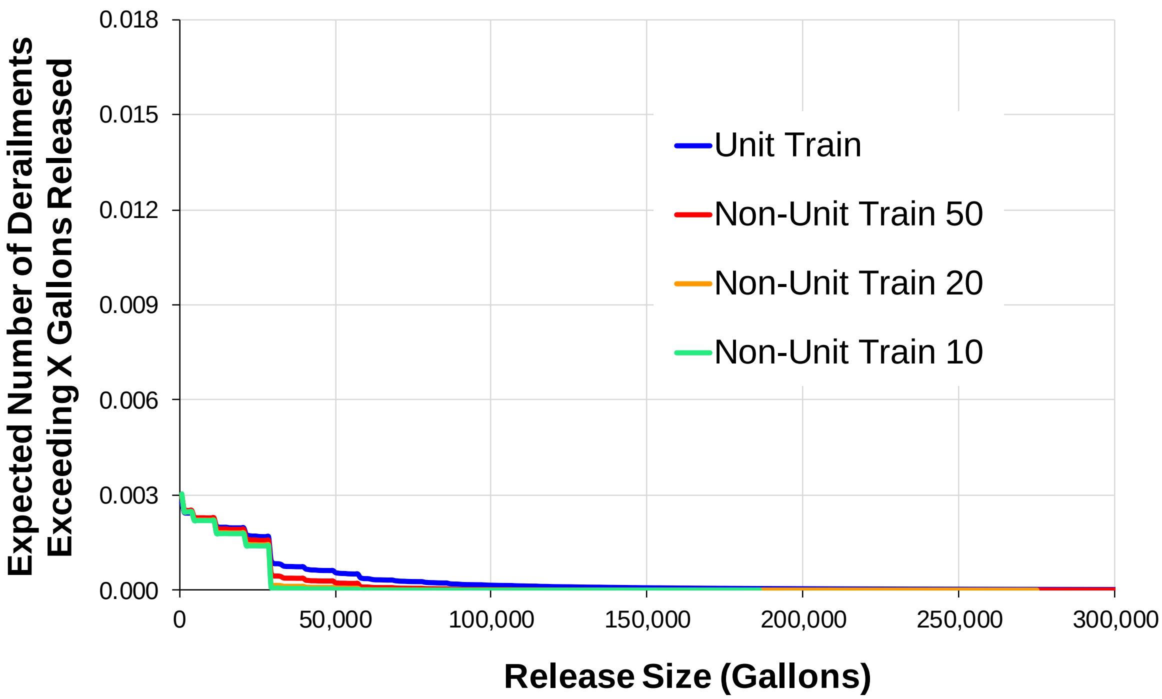

(b)

Figure 3.7: Inverse Cumulative Distribution of Annual Expected Number of Derailments by Quantity Released for (a) DOT 111 Tank Cars and (b) DOT 117 Tank Cars

Table 3.7: Summary Statistics for Distributions of Quantity Released

Expected Quantity Released per Trip (Gallons)

		Unit Train	Non-Unit Train 50	Non-Unit Train 20	Non-Unit Train 10
DOT 111	Expected Value	6.3	2.7	1.0	0.5
	Variance	1.38×E6	2.33×E5	4.24×E4	1.56×E4
DOT 117	Expected Value	1.4	0.5	0.2	0.1
	Variance	1.43×E5	1.78×E4	4.46×E3	2.00×E3

Expected Annual Expected Quantity Released (Gallons)

		Unit Train	Non-Unit Train 50	Non-Unit Train 20	Non-Unit Train 10
DOT 111	Expected Value	462.9	393.9	360.7	354.6
	Variance	1.00×E8	3.39×E7	1.53×E7	1.12×E7
DOT 117	Expected Value	101.0	69.0	57.5	55.2
	Variance	1.04×E7	2.60×E6	1.62×E6	1.46×E6

Conclusions

In this chapter, I compared the risk associated with transporting the same number of tank cars annually via unit trains or manifest trains with different numbers of tank cars per trip using DOT 111 and DOT 117 tank cars. The metrics used to assess risk are the number of tank cars derailed, the number of tank cars releasing, and the quantity released. These metrics each had similar distributions and the same qualitative results, but the magnitude of difference between scenarios varied with the use of different risk metrics.

For risk per trip, unit trains had higher risk because there are more tank cars per consist. For annual risk, unit trains had lower expected number of derailments and release incidents, and higher expected value and variance for number of tank cars derailed and releasing. Safer tank cars such as DOT 117s do not reduce the risk of being involved in a derailment, but they do reduce the expected number of releases and the quantity released by over 75% compared to the DOT 111s.

Future Work

This chapter is intended to provide a preliminary understanding of the tradeoffs between the use of unit trains and manifest trains for transport of hazardous materials. Some limitations in this research remain; for example, tank cars were assumed to be randomly distributed in the train, but tank car positions affect risk (Liu, 2017). Future work should consider the tank car positions in the train that generate the highest and the lowest risk to provide upper and lower bounds for the effect on risk.

Another limitation is that all the trains were assumed to use the same route. However, unit trains may use more direct routes than manifest trains thereby reducing their exposure to derailments. Manifest trains also require more time spent in classification yards where they are exposed to additional potential incidents. Even though the expected number of releases within yards is relatively small, the consequence of these accidents may be a concern if they are located near population centers. This yard component of risk for manifest trains was not accounted for in the analysis in this chapter but should be considered in a more holistic analysis.

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CHAPTER 4: EFFECT OF IMPLEMENTATION POLICIES FOR SAFER TANK CARS ON TRANSPORTATION RISK OF TOXIC INHALATION HAZARD MATERIALS

Introduction

In 2009, the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) promulgated a rule requiring all tank cars built after 2009 for transportation of toxic inhalation hazard (TIH) / poisonous inhalation hazard (PIH) materials to be compliant with new, interim DOT design standards (PHMSA, 2009*)*. Cars built in compliance with these new, safer, interim standards came to be known as "I-Cars". At that time, it was estimated that I-Cars reduce the probability of release if they were derailed in a Federal Railroad Administration (FRA) reportable mainline accident (conditional probability of release, aka CPR), by about 50% compared to the existing tank cars (aka "Legacy Cars") used to transport TIH materials (ATCCRP, 2016). Meanwhile, a new public-private collaborative research effort, the Advanced Tank Car Collaborative Research Program (ATCCRP), was launched with the objective of developing a new, substantially safer, final tank car design that was intended to supersede the I-Car. PHMSA specified that I-Cars would have a 20-year allowable life, but placed no restrictions on continued use of the existing fleet of legacy tank cars to transport TIH materials (PHMSA, 2009). The 20-year allowable life of the I-Cars was less than the normal 50-year life for tank cars. PHMSA's intent was to set standards on an interim basis "*until such time as final performance standards are developed and tank cars are available meeting such standards*" (PHMSA, 2009). In so doing, PHMSA created a disincentive to implementation of the I-Cars (AAR, 2016).

Aiming to achieve higher tank car safety standards, the ATCCRP conducted extensive research over the next eight years, including modeling, physical testing, simulation, and statistical analysis on a broad range of tank car elements and design considerations. This program developed a great deal of new and useful information that has advanced the understanding of tank car safety design; however, as the work of the ATCCRP progressed, it became evident that the program would not develop a specification that was both substantially safer than the I-Cars and reasonable from an economic and manufacturability standpoint (ATCCRP, 2016). Consequently, the ATCCRP partners submitted a petition to the PHMSA in 2016 requesting that the I-Car be made the permanent standard design for tank cars transporting TIH materials (ATCCRP, 2016). ATCCRP research would continue with the objective of identifying incremental improvements that could be incorporated into ongoing updates and improvements in tank car safety under the normal processes of the PHMSA and the Association of American Railroads (AAR) Tank Car Committee. In 2017, the PHMSA determined that the petition submitted by the ATCCRP merits consideration in future rulemaking (PHMSA, 2017). Currently, the industry is awaiting the final decision from PHMSA, and discussions about plans and schedule to phase in I-Cars are ongoing.

In this chapter, I consider several questions stemming from the PHMSA's decision in 2009 to defer action on a final specification for TIH tank cars. I present a risk analysis methodology and results related to the general question of how much the risk would be reduced under varying implementation scenarios for the new I-Cars. I also compare the results of hypothetical scenarios to the current, attrition-based implementation plan for I-Cars that is close to the actual effect of the rulemaking in 2009 requiring new tank cars to be compliant with I-Car standards. In particular, three questions were of interest:

1. In 2009, what is the estimated risk differential under various possible phase-in strategies of I-Cars compared to continuing the use of legacy tank cars without any restrictions?
2. In 2012, how much safer would a new tank car design produced by the ATCCRP have had to be to compensate for the additional risk incurred due to delaying onset of a 10-year implementation of the I-Car beginning in 2009?
3. What is the estimated risk associated with different phase-in plans being considered in 2018?

Research Objective

I used a Network Risk Analysis model to quantify the risk of transporting TIH materials. Several key metrics were calculated under varying implementation scenarios, including number of derailments involving TIH tank cars, number of TIH tank cars that released in these accidents and the estimated population affected. The objective is to provide a risk analysis framework and reasonable risk estimates to evaluate past decisions and inform decision makers regarding future implementation plans.

Methodology

The risk analysis method used railroad traffic data and a Network Risk Analysis model that combines network route information, spatial population data and the Multiple Tank Car Release (MTCR) model to estimate the total population affected. This chapter investigates the risk associated with transporting the top two TIH commodities by volume, ammonia and chlorine (AAR, 2016).

To estimate the probability of a release, a risk model was used that incorporated the MTCR model, along with railroad route, track characteristics and population. The MTCR model uses three principal inputs – train characteristics, track characteristics, and the conditional probability of release (CPR) of tank cars – to estimate several probability distributions related to derailment caused events that can lead to a release. Further details can be found in Liu et al. (2014). The model output includes the probability distribution of the number of tank cars releasing using the following equation (Liu et al., 2014):

$$P(X_R) \approx \sum_{X_D=0} \left\{ P(X_R|X_D) \left\{ \sum_{X=0} P(X_D|X) \left[\sum_{K=1} P(X|K) POD(K) \right] \right\} \right\}$$

where:

K = point of derailment (POD) (position of first car derailed)

POD(K) = probability distribution of point of derailment

X = number of cars (tank cars and non-tank cars) derailed

P(X|K) = probability distribution of number of cars derailed given point of derailment

X_D = number of tank cars derailed

$P(X_D|X)$ = probability distribution of tank cars derailed given total number of cars derailed

X_R = number of tank cars releasing

$P(X_R|X_D)$ = probability distribution of tank cars releasing given number of tank cars derailed

$P(X_R)$ = probability of X_R number of tank cars releasing per train trip on a route

Train Characteristics

Waybill data from the AAR TRAIN II database for ammonia and chlorine traffic in 2016 were used to estimate train characteristics. Each waybill entry represents a loaded tank car shipment, of which there were 33,144 and 24,428 for ammonia and chlorine respectively in 2016. Previous risk analyses used a car-mile based derailment rate and car-specific information from waybill data to obtain the risk of derailment of a single tank car (Saat, 2009). The MTCR model was developed to estimate the distribution of number of tank cars derailed and releasing and is thus more accurate when multiple cars in a train derail and release. Instead of relying solely on tank car-specific information, the MTCR model also incorporates the characteristics of a train. To obtain train-specific information, cars with the same origin and destination (O-D) pair on the same day were assumed to travel in the same trains.

Tank cars with the same O-D pair in the same train are referred to collectively as a “cut” in this research. Using this approach, the frequency distribution of tank cars being placed in different cut sizes was developed (Figure 4.1). Chlorine travels in single tank cars about three times more often than ammonia, and ammonia most frequently travels in cut sizes of five.

Other train-specific information was based on average values for Class I railroads (AAR, 2015). For example, train length was assumed to be 76; and the average weight of all other cars, including both loaded and empty cars, was assumed to be 163,600 lbs. The weight of loaded legacy tank cars was assumed to be 263,000 lbs., and 286,000 lbs. for I-Cars, based on the respective maximum gross rail load (GRL) permitted (FRA, 2011). In the analysis, trains were assumed to have three locomotives, each weighing 374,000 lbs., although this assumption has little effect on the results.

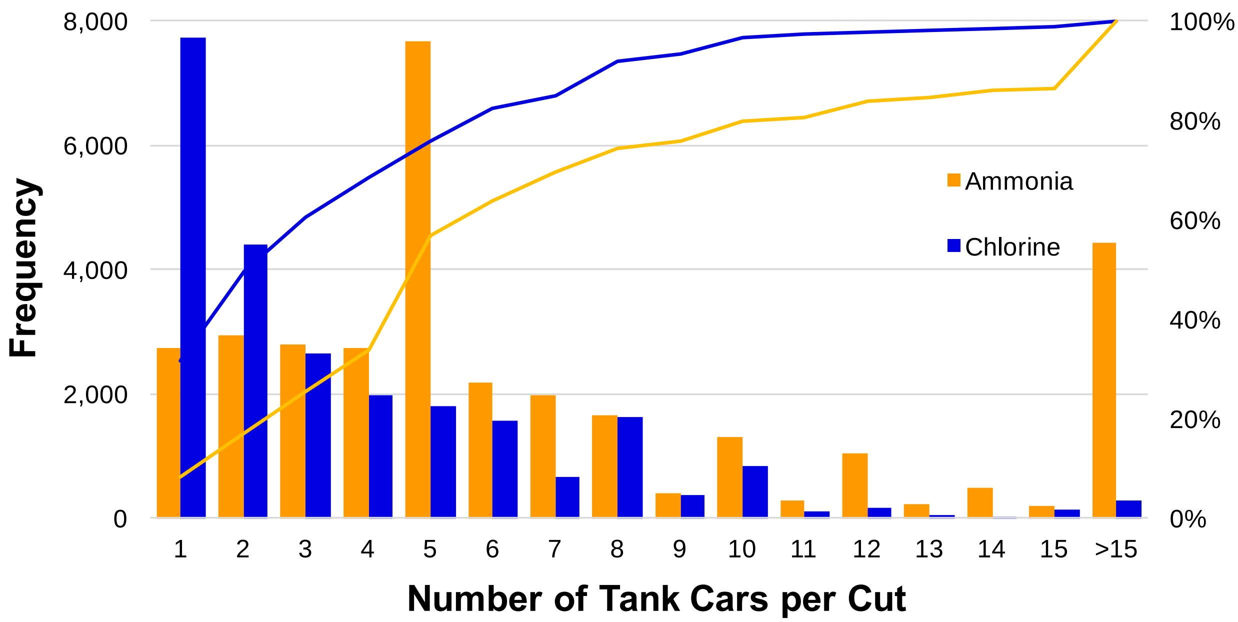


Figure 4.1: Frequency Distribution of Number of Ammonia and Chlorine Tank Cars Per Cut

Route Characteristics

For route characteristics, O-D pairs from traffic data were input into PC*Miler|Rail, a routing software, to generate the standard point location codes (SPLCs) of intermediate stations. SPLCs were then used to generate a route for each train in ArcGIS, which is a geographic information system that can perform spatial analysis. Rail line maps from the National Transportation Atlas Database (NTAD) (DOT, 2017), and US census data from Topologically Integrated Geographic Encoding and Referencing (TIGER) data (U.S. Census Bureau, 2017) were loaded as layers, from which route characteristics including track segment ID, traffic, length, and population density near each track segment could be obtained. By mapping the track segment ID to the database provided by railroads, and supplementing it with data from system timetables, additional track characteristics such as FRA track class and method of operation (whether the territory is signaled or dark) were obtained for each segment ID. Information on track class, method of operation, and traffic was required to estimate the segment-specific derailment rate based on Liu et al.'s (2017) three-factor derailment model.

Conditional Probability of Release (CPR)

Different tank car specifications safety designs have different CPR values if they are derailed in an FRA-reportable mainline accident (ATCCRP, 2016). This paper focuses on comparison of the specifications for legacy tank cars and I-Cars for ammonia and chlorine (Table 4.1). Switching to I-Cars for ammonia and chlorine substantially improves safety because the CPR is reduced by over 50% for both commodities.

Table 4.1: Tank Car Specifications and CPR (ATCCRP, 2016)

Product	Tank Car Spec	Head Thickness (inches)	Shell Thickness (inches)	Head Shield	Shell Inside Diameter (inches)	CPR	Percent Improvement
Ammonia	112J340W	0.625	0.625	Full	119	0.033	
	112J500I	0.900	0.900	Full	116.75	0.016	52%
Chlorine	105J500W	0.812	0.775	No	100.45	0.042	
	105J600I	0.954	0.954	Full	100.45	0.020	53%

Population Affected

Combining train information, route information, and the CPR for the legacy tank car and I-Car specifications, the MTCR model produces estimates of the probability of derailment and release on each track segment for a train. The population density along a buffer area adjacent to each rail line segment was calculated using ArcGIS. The size of this buffer was based on the size of the protective action zone (PAZ) for each chemical recommended by PHMSA's Emergency Response Guidebook (ERG) (2016). The size of the PAZ is affected by the wind speed and whether a release occurs during the day or night. For purposes of this analysis, I assumed moderate wind speed and that accidents are equally likely to happen during the day or night. The width of ERG PAZ buffer was calculated to be 1.1 and 4.8 miles for ammonia and chlorine respectively, and the corresponding areas were 1.3 and 23.68 square miles, respectively. The Network Risk Analysis model estimates total population affected by summing the product of the probability of release, the population density, and the area affected over all track segments and trains.

Results

Using this risk analysis method, the estimated risks associated with ammonia and chlorine traffic in 2016 were developed (Table 4.2). The tank car specification has a small effect on estimated number of derailments and the expected number of tank cars derailed. This is because the GRL of I-Cars is higher than that of legacy tank cars, and the current derailment frequency estimation method is based on ton miles. Consequently, the higher GRL for I-Cars results in a slightly higher rate per car. Offsetting this is that I-Cars have a larger capacity, which reduces the number of shipments and therefore exposure to derailments. The annual traffic was adjusted to account for the higher capacity of I-Cars. Comparing the capacity of randomly sampled I-Cars and legacy tank cars, the average capacity increase was about 1.4% for ammonia and 4.3% for chlorine.

Table 4.2: Estimated Risks of Ammonia and Chlorine Traffic in 2016

Product	Tank Car Type	Expected Derailments	Expected Tank Cars Derailed	Expected Releases	Population Affected
Ammonia	Legacy	0.324	0.164	0.023	18
	I-Car	0.330	0.169	0.013	10
Chlorine	Legacy	0.366	0.133	0.032	476
	I-Car	0.353	0.129	0.014	211

For the purpose of this study, I assumed that traffic remained constant during the study period. Another factor I considered was that in 2016, 15% of ammonia tank cars and 28% of chlorine tank cars were I-Cars, reflecting the attrition-based phase-in of cars constructed since the 2009 rulemaking. I assumed that the phase-in was linear, and that traffic was evenly distributed among different tank cars. For example, from 2009 to 2016, I-Cars replaced 28% of chlorine tank cars, so the attrition-based phase-in rate used for chlorine was 4% per year, which was the average rate over the 7-year period from 2009 to 2016. Based on these results and assumptions, I compared the risk of different implementation scenarios.

Policy Scenarios in 2009

The first objective of this chapter is to understand the risk of transporting TIH materials under various phase-in strategies of I-Cars. With the development of I-Car specifications in 2009, AAR proposed a 10-year phase-in of I-Cars (AAR, 2008), while PHMSA proposed an attrition-based phase-in of I-Cars with the expectation that safer tank cars would be available shortly after 2012. However, as discussed above, the ATCCRP research eventually made it apparent that a substantially safer design was impractical, so the actual effect of the rulemaking in 2009 was close to the second option represented in Figure 4.2.

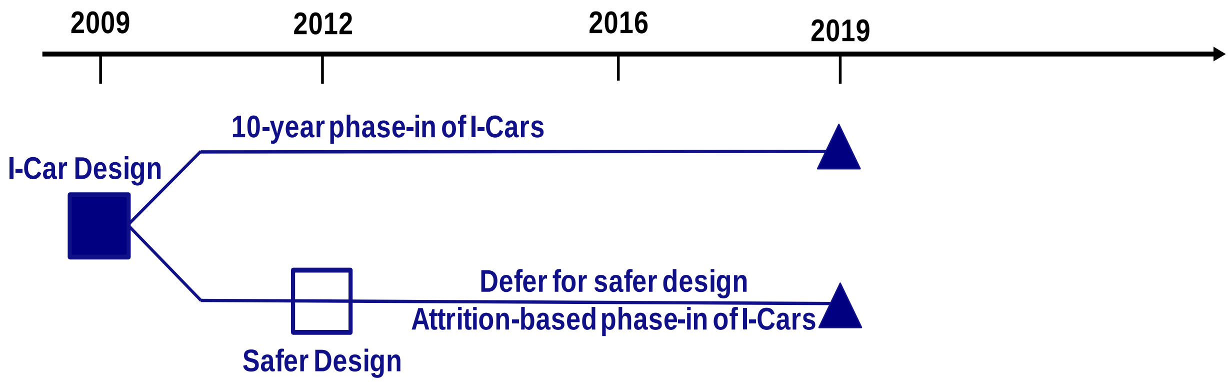
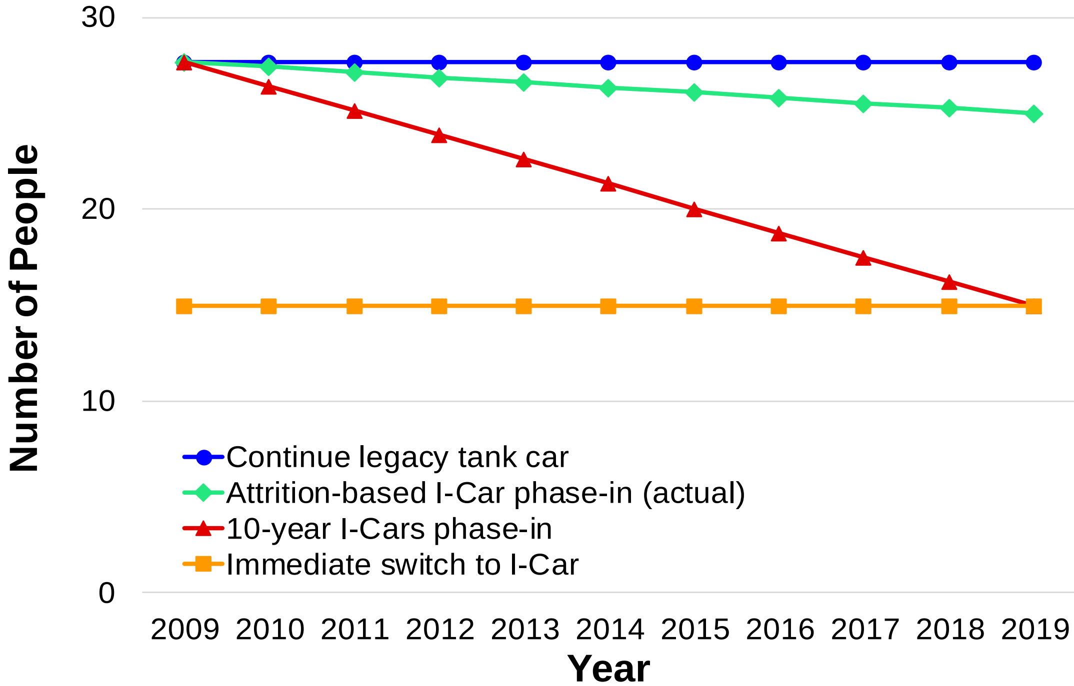


Figure 4.2: Phase-In Options in 2009

I considered eight scenarios for the period 2009-2019 based on four different phase-in options and two different assumptions about the derailment rate. The four phase-in policy options considered were: continued use of legacy tank cars, a 10-year phase-in of I-Cars, the actual attrition-based phase-in rate observed in response to the regulation, and for comparison purposes, an immediate implementation of I-Cars in 2009. Regarding the derailment rate, two options were considered: a static derailment rate with no change since 2009, and the actual, declining Class I railroad derailment rate observed since 2009 (Liu, 2015). The estimated population affected was calculated for ammonia and chlorine for the four phase-in options with both static and decreasing derailment rate (Figures 4.3 and 4.4).



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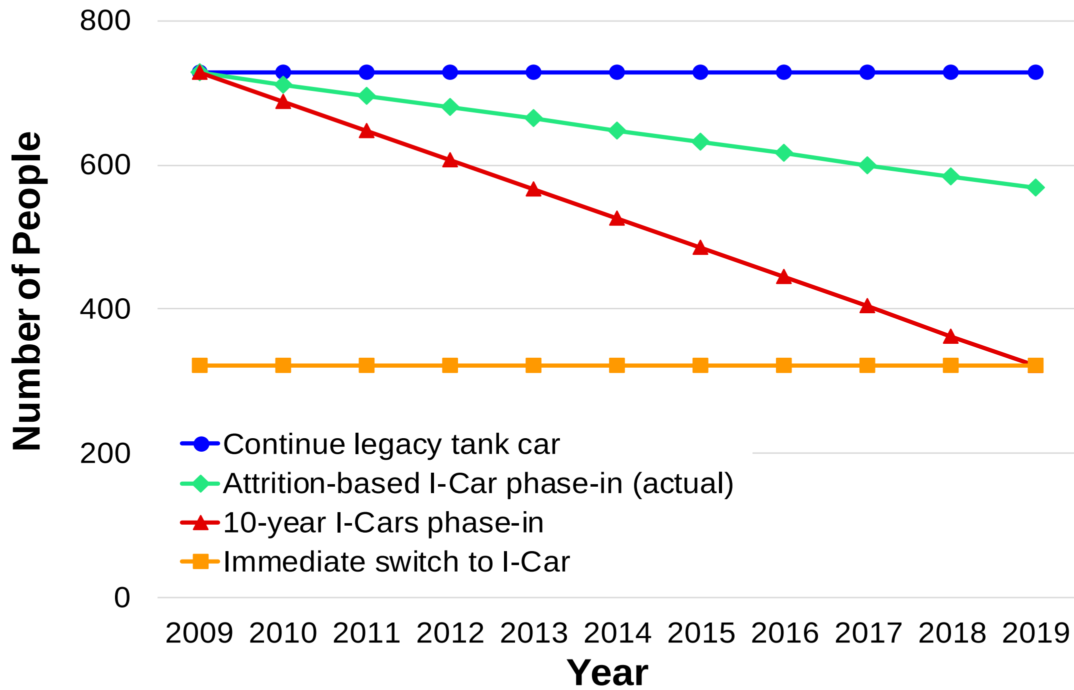

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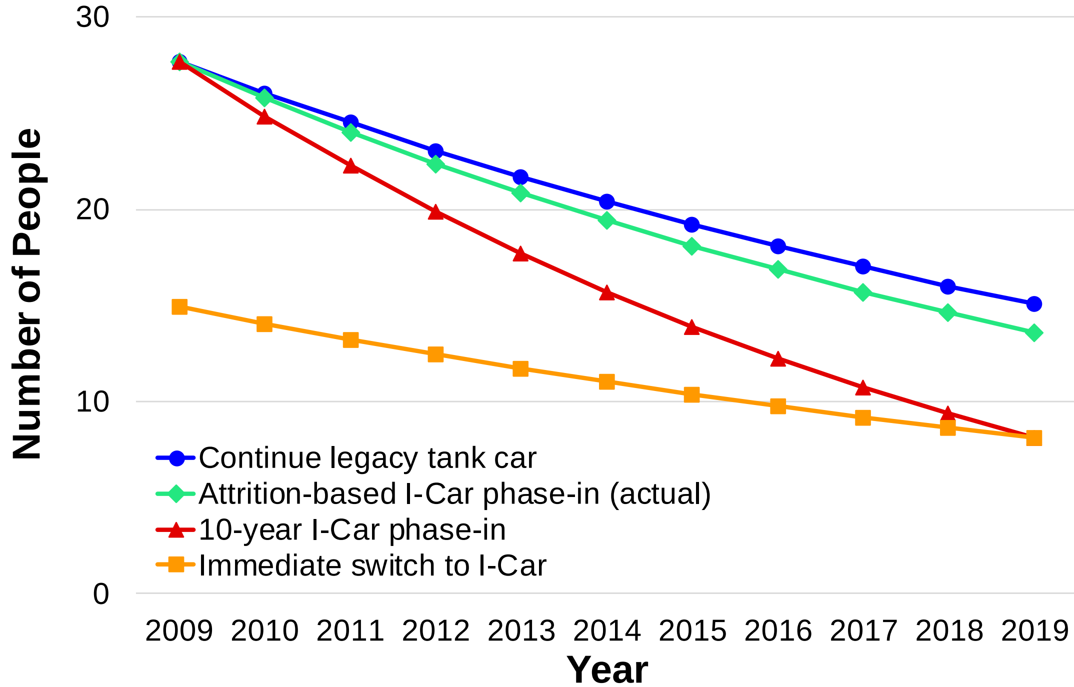
Figure 4.3: Estimated Annual Population Affected by (a) Ammonia and (b) Chlorine With Static Derailment Rate



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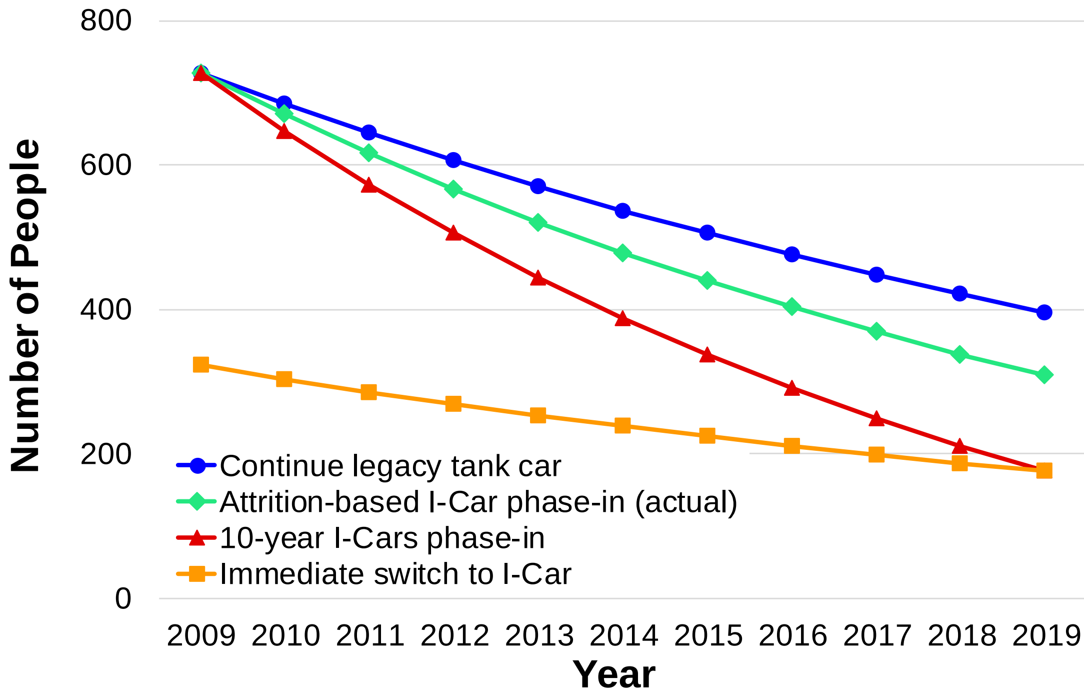


(b)

Figure 4.4: Estimated Annual Population Affected by (a) Ammonia and (b) Chlorine With Decreasing Derailment Rate

Over the 11-year period, the cumulative expected risks were evaluated based on three metrics: the expected number of tank cars derailed, the expected number of releases, and the population affected (Table 4.3). The four different policy scenarios have minimal effect on the expected number of tank cars derailed because as previously discussed, the use of different tank car specifications has little effect on the derailment frequency. However, different tank car specifications substantially affect the probability of release, which is reflected in the difference in the expected number of releases and the corresponding population affected under the various policy scenarios. If all ammonia and chlorine traffic was transported in I-Cars from 2009 to 2016, the expected number of releases and the population affected would have been reduced by about 46% for ammonia, and 56% for chlorine compared to continued use of legacy tank cars. A 10-year phase-in of I-Cars would have reduced the risk metrics by about 20% for ammonia and 25% for chlorine. The linear attrition-based phase-in, which approximates the actual effect of the rulemaking in 2009, reduced the population affected about 5% and 10% for ammonia and chlorine respectively.

The declining derailment rate had the effect of reducing the marginal benefit of implementing the I-Car. For example, if the derailment rate had remained static, the 10-year phase-in of ammonia I-Cars in 2009 would have resulted in a 23% reduction in risk, whereas the same comparison with the declining derailment rate would have been a 20% reduction. The combined effect of both the actual decline in derailment rate and the 10-year implementation of the I-Car would have reduced estimated risk by about 40% for ammonia and 43% for chlorine.

Table 4.3: Estimated Risks of Ammonia and Chlorine Traffic from 2009 to 2019

Number of Tank Cars Derailed

Derailment Rate	Product	Legacy Tank Cars	I-Cars	Attrition-Based Phase-In	10-Year Phase-In
Static	Ammonia	2.76	2.77	2.77	2.77
	Chlorine	2.25	2.18	2.23	2.21
Decreasing	Ammonia	2.07	2.08	2.08	2.08
	Chlorine	1.69	1.64	1.68	1.67

Number of Releases

Derailment Rate	Product	Legacy Tank Cars	I-Cars	Attrition-Based Phase-In	10-Year Phase-In
Static	Ammonia	0.403	0.217	0.383	0.310
	Chlorine	0.539	0.239	0.480	0.389
Decreasing	Ammonia	0.303	0.163	0.290	0.241
	Chlorine	0.405	0.180	0.366	0.306

Population Affected

Derailment Rate	Product	Legacy Tank Cars	I-Cars	Attrition-Based Phase-In	10-Year Phase-In
Static	Ammonia	305	164	290	235
	Chlorine	8,008	3,545	7,128	5,777
Decreasing	Ammonia	230	124	220	183
	Chlorine	6,018	2,664	5,437	4,544

Policy Scenarios in 2012

Another objective of this chapter is to ask how much safer a new tank car design produced by the ATCCRP in 2012 would have needed to be to compensate for the additional risk incurred due to delaying onset of a 10-year implementation of the I-Car immediately beginning in 2009. To address this question, the risk outcomes of the first two options in Figure 4.5 were investigated. For this analysis a 50-year period was used based on the maximum life span of a tank car. The outcome of the third option in Figure 4.5 will be addressed in the next section.

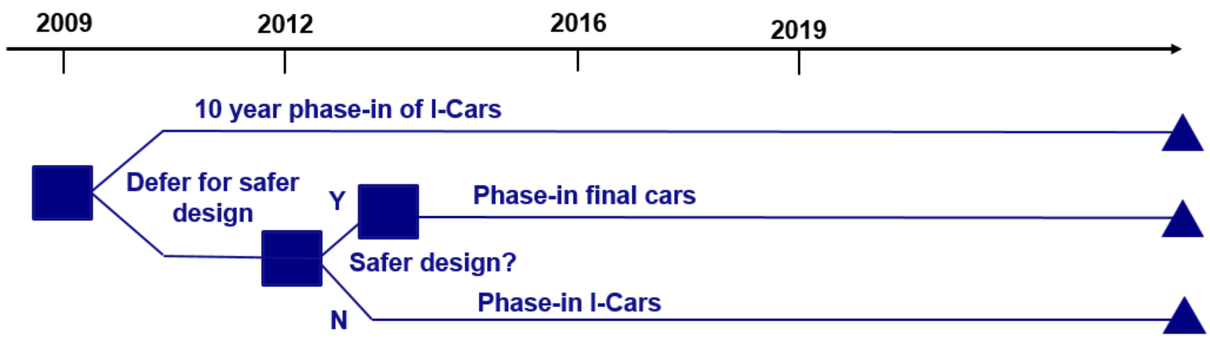


Figure 4.5: Phase-In Options in 2012

The green line (diamond symbol) in Figure 4.6 gives the cumulative expected population affected by ammonia traffic adjusted for decreasing derailment rate with a 10-year phase-in of I-Cars beginning in 2012; the red line (triangle symbol) shows the same thing, except with a phase-in beginning in 2009. Because of the delayed implementation of I-Cars, the cumulative population affected shown by the green line will always be higher than the red line. By scaling the population affected to adjust for the effect of safer tank cars, it is possible to make the green line converge with the red line, which is denoted by the blue line (circle symbol). This means that to offset the increased risk from delaying the 10-year phase-in from 2009 to 2012, the newer tank car would need to be 15.7% safer than I-Cars to make the total expected population affected equal at the end of the study period. If the phase-in period in 2012 was shorter, such as five years, the newer tank car would only need to be 2.0% safer than I-Cars.

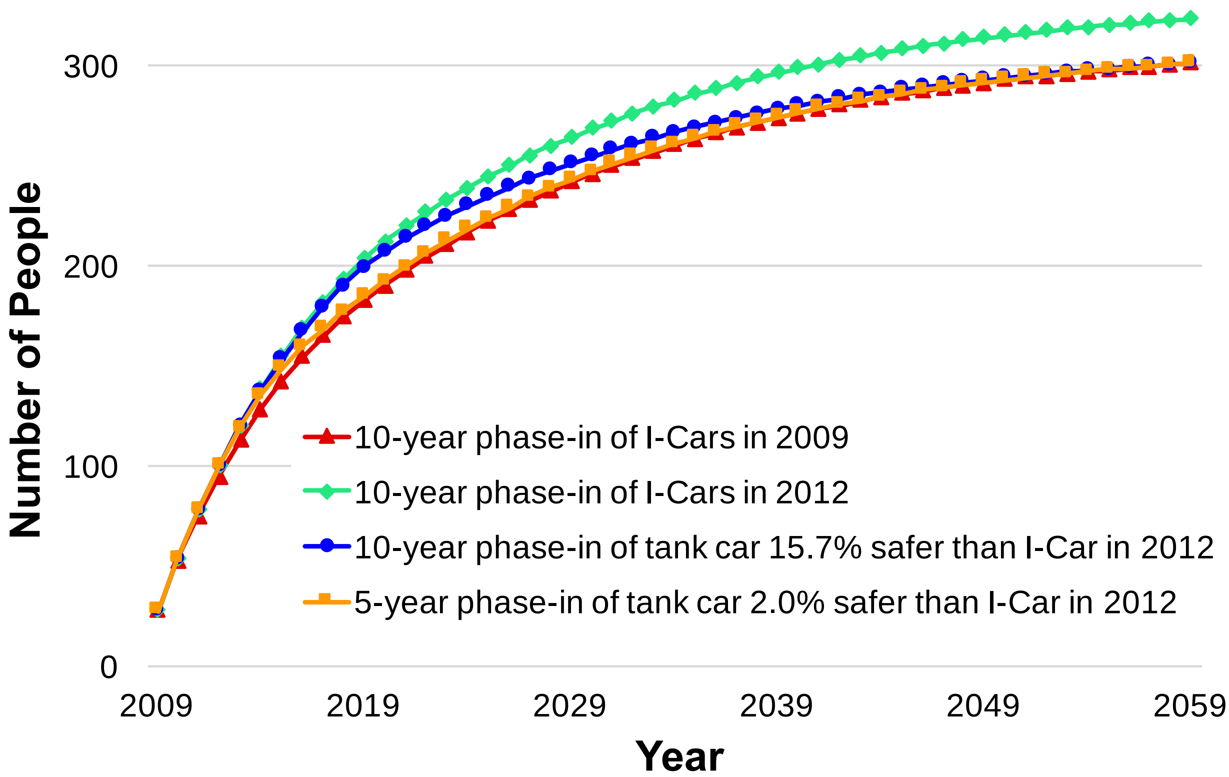


Figure 4.6: Estimated Cumulative Estimated Population Affected by Ammonia Traffic

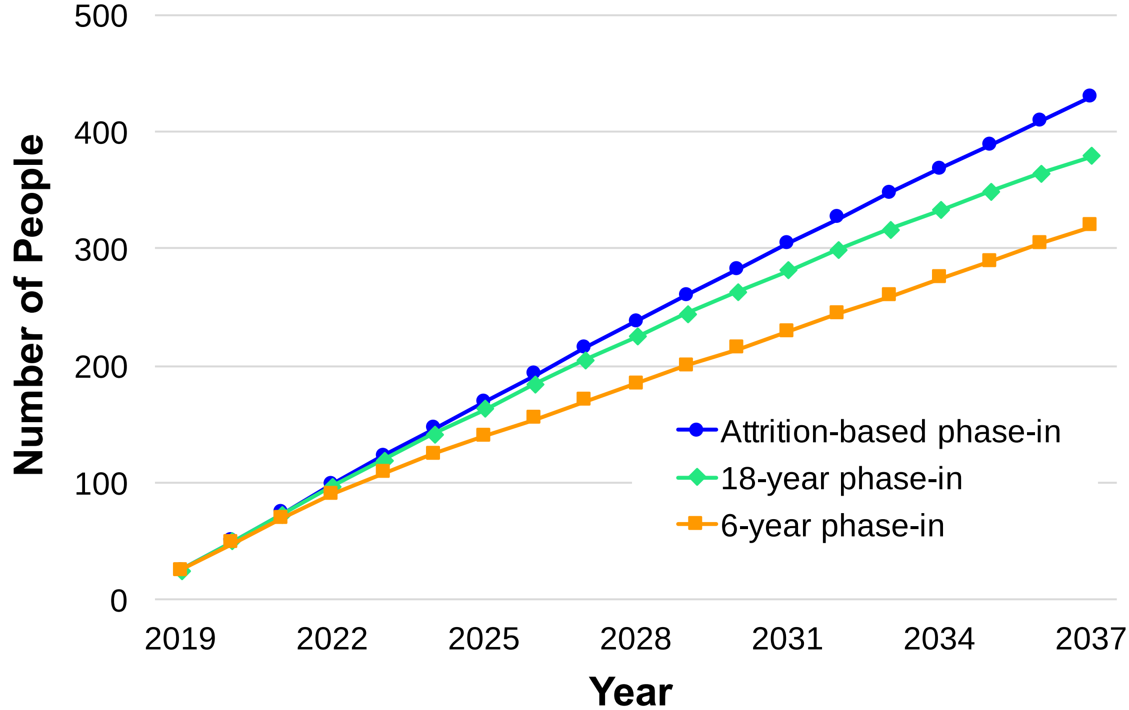
Table 4.4 summarizes the results addressing the question of how much safer the newer tank car needed to be to offset the risk due to delaying the implementation of I-Cars. The higher the percentage, the more robust the new tank cars need to be, which would likely lead to a higher cost and a reduced capacity if building them was feasible. As discussed earlier, with decreasing the derailment rate, deferring implementation of safer tank cars reduces the marginal benefit. Thus, the longer the implantation is deferred, the more difficult it is to equal the total safety. The newer tank cars for ammonia would need to be more than 15% safer with a decreasing derailment rate to justify deferring the 10-year phase-in from 2009 to 2012, as compared to about 5% safer if the derailment rate had remained static. It is also possible to compensate for deferring the safer tank car implementation by shortening the phase-in period. For example, with a 5-year phase-in in 2012, the newer tank car specifications are not required to be substantially safer than I-Cars for the total population affected to be the same as a 10-year phase-in in 2009.

Table 4.4: Safer Tank Car Required to Offset the Effect of Delaying Implementation of I-Cars

Derailment Rate	Product	10-Year Phase-In	5-Year Phase-In
Static	Ammonia	5.2%	0.3%
	Chlorine	6.6%	-0.1%
Decreasing	Ammonia	15.7%	2.0%
	Chlorine	19.7%	0.4%

Policy Scenarios in 2019

Following PHMSA's acceptance of the petition submitted by the ATCCRP in 2017, the industry is awaiting the new rulemaking on the phase-in policy. There are two principal proposals being considered, a 6-year phase-in and an 18-year phase-in. The method described in the preceding sections was applied to evaluate these alternatives in terms of future risk. The population affected was estimated under these two policy scenarios as well as the current attrition-based phase-in (Figures 4.7 and 4.8, Table 4.5).



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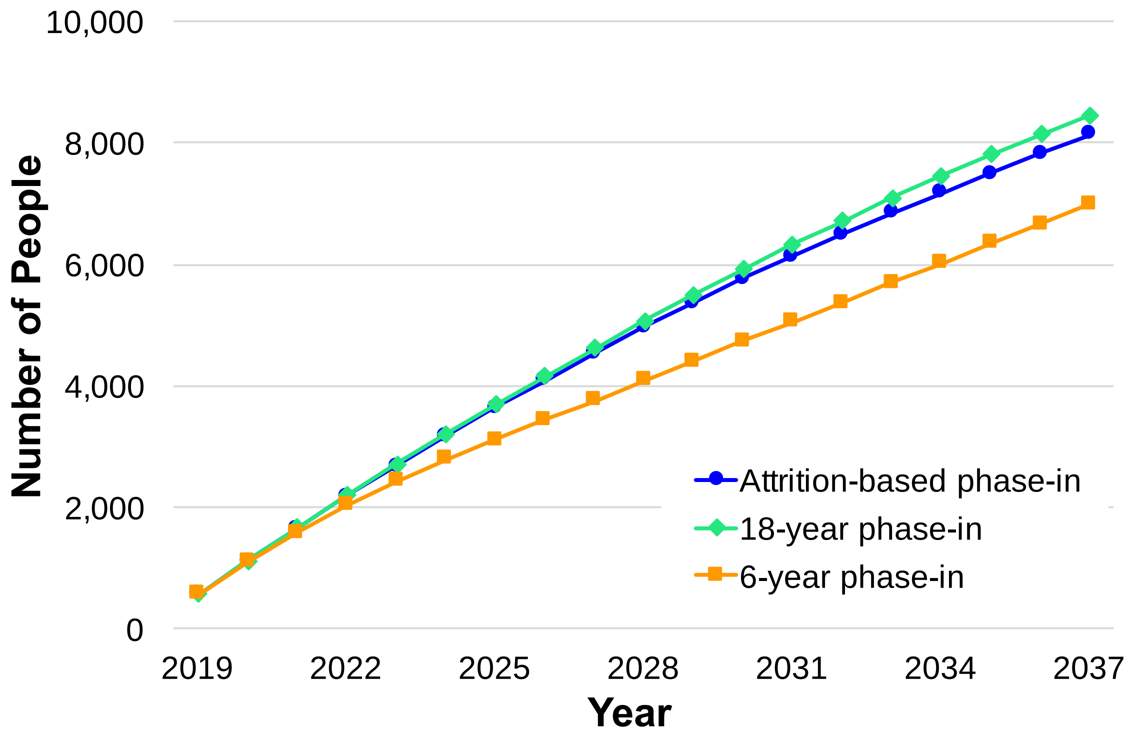
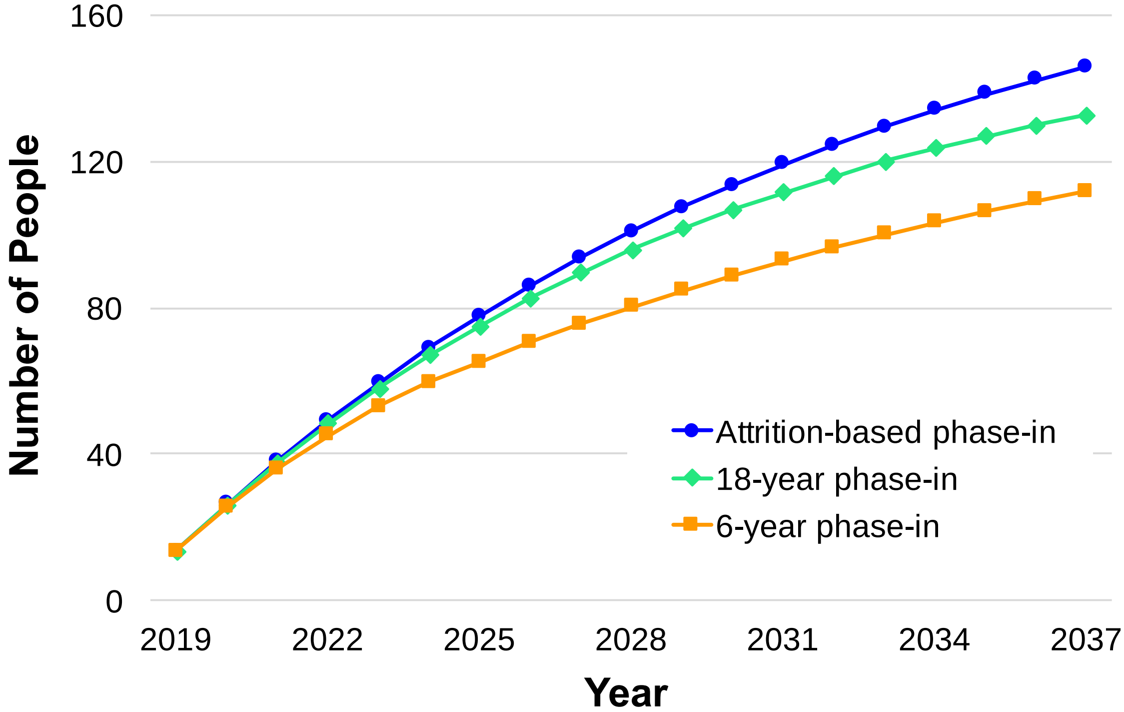
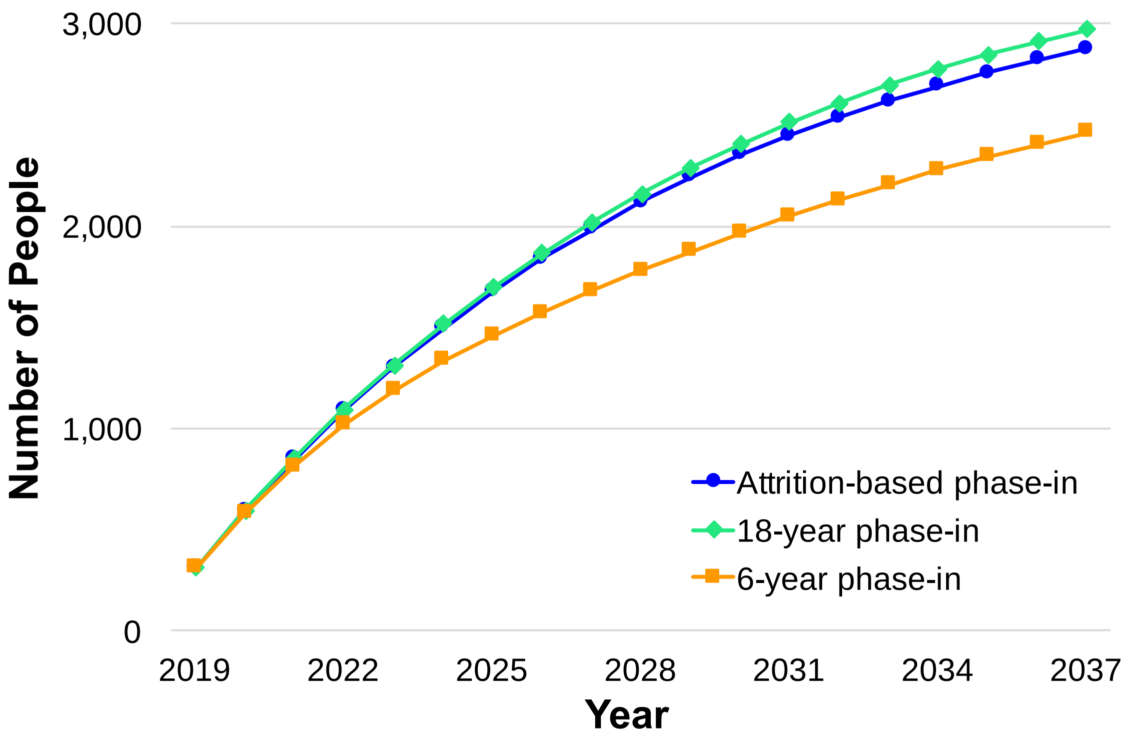


(b)

Figure 4.7: Estimated Cumulative Population Affected by (a) Ammonia and (b) Chlorine With Static Derailment Rate



(a)



(b)

Figure 4.8: Estimated Cumulative Population Affected by (a) Ammonia and (b) Chlorine With Decreasing Derailment Rate

The 18-year phase-in rate is actually slightly slower than the current attrition-based phase-in rate for chlorine, which is the reason that the total population affected is higher with an 18-year phase-in (Table 4.5). Based on this estimation, the 18-year phase-in will reduce the population affected by ammonia traffic by about 10% and will not decrease the population affected by chlorine. A 6-year phase-in, on the other hand, will reduce the population affected by ammonia and chlorine traffic by about 20% and 14% respectively compared to having an attrition-based phase-in.

Table 4.5: Estimated Population Affected Under Varying Policy Scenarios in 2019

Derailment Rate	Product	Attrition-Based Phase-In	6-Year Phase-In (Population Affected, Percent Reduced)		18-Year Phase-In (Population Affected, Percent Reduced)	
Static	Ammonia	430	319	26%	380	12%
	Chlorine	8,136	6,984	14%	8,458	-4%
Decreasing	Ammonia	146	112	23%	133	9%
	Chlorine	2,876	2,462	14%	2,968	-3%

Conclusion and Future Work

This research evaluates the safety benefit of implementing safer tank cars under varying policy scenarios by integrating data from several sources and performing a spatial analysis using GIS. The results provide a quantitative approach to understand the effect of several policy questions related to implementation of more damage-resistant tank cars for transportation of TIH materials.

The results show that I-Cars reduce population affected by about 50%. A 10-year phase-in of I-Cars in 2009 would have reduced population affected by about 20% compared to continuing using legacy tank cars, while the attrition-based phase-in that actually occurred reduced risk by about 5% and 10% for ammonia and chlorine respectively. In addition, by deferring implementation of safer tank cars, the marginal benefit is reduced due to the overall reduction in derailment rate. This is the reason that with decreasing derailment rate, a ten-year phase-in in 2012 would require substantially safer tank car specifications (over 15% safer than I-Car) to compensate for the risk that could have been reduced by delaying onset of a 10-year implementation of the I-Car immediately beginning in 2009, as compared to about 6% safer with static derailment rate.

In conducting this research, I made several assumptions to enable development of the estimates presented here. The effect of these assumptions could be further refined in future research. For example, this research only considered mainline derailments, the effect of yard, sidings and industry trackage could be considered in future work. The effect of collisions could also be incorporated into these risk analyses. The MTCR model also assumes that tank cars are randomly positioned in the train. However, tank cars in a cut may often travel together in trains between origin and destination. Thus, the in-train placement of tank cars could be modeled more realistically. This research also assumed a linear phase-in of I-Cars, but this could be refined using information on the actual demographics of the tank car fleet. Using the year built and average life span of tank cars, the percentage of tank cars replaced each year could be more accurately estimated. The top two TIH commodities, ammonia and chlorine, were evaluated based on traffic from 2016. Future work should include the other TIH materials using actual and estimated traffic.

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CHAPTER 5: CONCLUSIONS AND FUTURE RESEARCH

In previous chapters, I focused on derailments and releases of hazardous materials, specifically discussing three topics related to this general theme: unit train loading condition, the effect of train configuration on risk and the safety benefit of implementation schedule for safer tank cars. In this chapter, I summarize the principal results, discuss some of the practical applications and implications for risk mitigation strategies and possible future research needs.

In Chapter 2, I found that loaded and empty unit train derailments have differences in derailment frequency, severity and causes. There were five times more loaded unit train derailments than empty unit train derailments recorded in the FRA REA database. Relevant traffic data are needed to determine whether there is a different derailment rate for the two loading conditions. The comparison of severity showed that loaded unit trains derailed significantly more cars than empty unit trains. Part of the difference in frequency and severity might be explained by the derailment causal analysis that found different distributions of causes for the two loading conditions. Three out of the top ten most frequent derailment causes for the two loading conditions were the same, suggesting that reducing the incidence of these causes will improve safety irrespective of the train loading condition. For example, broken rails or welds were the most frequent cause for loaded unit trains and the second most frequent cause for empty unit trains, and this cause often led to severe accidents in both loading conditions. Mitigation strategies targeting this cause will likely be more cost-effective because these types of accidents are both frequent and severe. The most frequent and severe causes of empty unit train derailments were extreme weather conditions such as tornadoes and extreme wind velocity.

Since empty trains are particularly susceptible to these types of accident, modification of operating practices for these trains when severe weather threatens may be of particular importance in managing risk.

In Chapter 3, I compared the risk associated with transporting the same volume of hazardous material traffic annually in a smaller number of unit trains, or distributed in a larger number of manifest trains. On a per trip basis, unit trains have higher average risk because there are more tank cars with hazardous materials per consist. For annual risk, more manifest trains are required to transport the same number of tank cars, which increases their exposure to derailments, resulting in relatively smaller, but more frequent derailments and releases. By contrast, fewer unit trains are needed, and the risk for these trains conforms to a low frequency, high consequence risk profile. I used three metrics to assess safety and risk, number of tank cars derailed, number of tank cars releasing, and quantity released. The annual expected value and variance for these risk metrics are higher for unit trains than manifest trains. As expected, DOT 117 tank cars derailed at about the same rate as DOT 111 tank cars, but they substantially reduce the probability of release and expected quantity released in all scenarios. Further refinement of this research would involve analysis of different tank car positions in trains. For example, tank cars from the same origin to the same destination in a manifest train may tend to be positioned together, whereas in my analysis the model assumed random and independent placement of tank cars in the train. The effect of different routes for unit versus manifest trains could also be investigated. In this study, I assumed that both train types used the same route, but in actuality unit trains might use more direct routes than manifest trains. Cars traveling in manifest trains also spend more time in classification yards where they experience additional handling and consequent exposure to additional accident risk. The methodology presented in this chapter could be adapted to evaluate risk for particular routes and train configurations.

In Chapter 4, I presented an approach to quantify the safety benefit of implementing safer tank cars under several different replacement schedules based on the proposals considered by railroads, chemical shippers, tank car companies, and government. The approach integrated traffic and routing data, spatial information and used the MTCR model. This approach improves upon previous work because it accounts for the number of cars in a train rather than simply relying on individual tank car derailment rate and release probability. In this research I also considered two derailment rate scenarios, one in which derailment rate remained static, and the other reflecting the declining derailment rate. In all scenarios I found that implementing safer tank cars sooner reduced risk, because with decreasing derailment rate, the marginal benefit of the safer tank cars declined as time progressed.

This research can provide insight to ongoing and future consideration of different policy options for phase-in of safer tank cars. Further research on this topic might consider the role of collisions, and accidents on other track types, such as sidings and yard tracks. Here again, in-train tank car placement could be modeled more realistically to account for tank cars in a cut. Another avenue for further research would be to use the actual demographics of the tank car fleet to estimate replacement period, rather than simply assuming a linear phase-in, as was done in this study. Future work could also evaluate other TIH commodities, the effect of differing amounts of traffic, and alternative routing.